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STABILIZATION OF SOILS FOR EROSION CONTROL ON CONSTRUCTION SITES

George Macha

PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

75-5

Interim Report

STABILIZATION OF SOILS FOR EROSION CONTROL
ON CONSTRUCTION SITES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

March 26, 1975

Project: C-36-50H

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-19-8

The attached Interim Report titled "Stabilization of Soils for Erosion Control on Construction Sites" has been authored by Mr. George Macha, Graduate Instructor in Research on our staff. The Report is on the HPR Part II Study "Soil Stabilization for Erosion Control". Dr. Sidney Diamond is principal investigator of the Study and directed the activity of Mr. Macha.

This publication reports the results of laboratory tests on erosion of soils under rainstorms when treated with small amounts of Portland Cement or hydrated lime. An evaluation of the benefits and the costs indicates that these soil stabilization treatments might provide economically viable means of minimizing erosion on construction sites.

The Report is presented to the Board for acceptance as partial fulfillment of the objectives of this research. The report will also be forwarded to ISHC and FHWA for review, comment and similar acceptance.

Respectfully submitted,

Harold L. Michael

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Associate Director

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16. Abstract

Small amounts (usually 1 percent by weight) of hydrated lime or of Portland cement were incorporated into 1 in. thick layers of soil by laboratory mixing, followed by standard Proctor compaction and curing in a humid chamber. The resulting specimens were tested for resistance to raindrop impact erosion in a laboratory rainfall simulator, using a standard rainstorm sequence of 3¼ in/hr intensity applied for 1 hr. on each of two successive days. For three Indiana soils tested, such treatments reduced erosion loss to almost zero; higher additions seemed to be required to stabilize a heavy montmorillonite clay soil. Hydrated lime required curing periods of the order of several weeks to be effective. Reduced compactive effort was found to result in slightly less resistance to erosion. Application of both lime and Portland cement to the surface of specimens in slurry form was found to be reasonably effective. Cement treatments did not interfere with germination or growth of grass. A brief survey of comparative costs indicated that lime or Portland cement treatments might provide economically viable means of erosion control on construction sites; however, no data was provided on the resistance of such stabilized soils to rill erosion caused by running water on steep slopes.

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STABILIZATION OF SOILS FOR EROSION CONTROL ON CONSTRUCTION SITES

Interim Report

Highlight Summary

The influence of small amounts (usually 1 percent by weight) of hydrated lime or of Portland cement in stabilizing soils against erosion caused by raindrop impact was investigated using four Indiana soils. The method of test involved measurement of soil eroded from small specimens in a "standard rainstorm sequence" of 3¼ inches of rainfall per hour for 1 hour on each of two successive days, applied from a laboratory rainfall simulator.

It was found that, for all but a heavy swelling clay soil, erosion loss was reduced to almost zero under this test by treatment with 1 percent Portland cement carefully mixed into a thin layer of surface soil, compacted to standard Proctor density, and cured for several days. Hydrated lime was found to be almost equally effective, but only after longer curing periods. If the soil was compacted only lightly the resistance to erosion decreased somewhat, but the treatments were still judged highly effective.

It was also found that the application of hydrated lime or Portland cement in slurry form could also provide effective resistance to raindrop impact erosion. Cement treatments, either mixed with the soil or applied in slurry form, did not interfere with the germination and growth of Alta fescue grass, and the possibility of combination erosion control treatments of light cement stabilization with permanent grass cover seems to exist. Lime mixed with soil did not permit establishment of grass.

A brief survey of relative costs appeared to indicate that these soil stabilization treatments might provide economically viable means of preventing erosion on construction sites.

The study provided no data on the resistance of soils stabilized in this fashion to reill erosion caused by running water on steep slopes.

Interim Report

STABILIZATION OF SOILS FOR EROSION CONTROL ON CONSTRUCTION SITES

by

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and the

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana
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ABSTRACT

Macha, George. MSCE, Purdue University, December, 1974. Stabilization of Soils for Erosion Control on Construction Sites. Major Professor: Sidney Diamond.

The effectiveness of small amounts (usually one percent by weight) of lime or of Portland cement in stabilizing various soils against raindrop erosion was investigated. A severe standard rainstorm sequence (3-1/4 inches per hour for one hour on each of two successive days) was applied to treated and to untreated soil specimens using a specially-designed rainfall simulator, and the soil removed was recovered and weighed. The stabilizer was either incorporated with the soil by mixing or was applied on the soil in slurry form. The specimens were compacted to Standard Proctor density, or by standardized reduced compactive efforts, and cured for 3, 7, and 28 days before testing. Stabilized specimens were also prepared incorporating grass seed and observations made on subsequent germination and growth of the grass.

It was found that erosion was reduced substantially with all of the methods used to almost zero values for many treatments on all but a heavy montmorillonite clay soil. Lime treatment conferred erosion resistance only after a somewhat longer curing period than did cement treatment, but the long term results were excellent. Erosion loss for stabilized soils compacted at reduced compactive efforts were, in general, satisfactorily low but slightly higher than companion specimens

compacted to full Proctor maximum densities. However, it was found that reduced compactive effort generally reduced the loss of unstabilized soil, a somewhat unexpected result.

Both lime and cement slurry applications to the surface of lightly-compacted specimens provided reasonably satisfactory erosion control, the lime slurries leaving a somewhat unsightly crust, however.

The results of this study reflect the action of raindrop impact, and resistance of stabilized soils to erosion caused by running water was not specifically studied.

It was found that the germination and growth of Alta fescue grass was compatible with both incorporated and slurry-applied cement treatments, and with lime treatment using slurry application, provided the slurry did not contact the seeds. Grass seeds did not germinate in contact with lime mixed into the soil.

A brief study of relative costs of lime and cement stabilization compared with other means of preventing soil loss suggested that these treatments might provide economically viable methods of preventing erosion loss on construction sites. It appeared that slurry applications would be cheaper than methods involving mixing, and that such treatment might be similar in cost to conventional hydroseeding of grass.

INTRODUCTION

Soil erosion on construction sites has become a major contributor to the sediment load carried by streams in many parts of the country. The results of accelerated erosion have led to serious economic consequences including premature silting of reservoirs, interference with natural river biota, and other environmentally-related consequences. There are also consequences on the construction sites themselves, including clogged channels and storm sewers, undercut pavements and pipelines, debris laden work areas, and formation of rills and eventual gullies on unprotected slopes. An illustration of this, taken from the site of collection of one of the soils used in this study is given in Fig. 1.

The risk of severe erosion is particularly great when a long delay elapses between the time the site is first opened up and natural cover removed and the time final cover, drainage, and vegetative protection are provided.

Efforts at minimizing the effects of erosion on construction sites have generally taken the form of provision of temporary catchment basins, diversion ditches, and other expensive means of confining the spread of the eroded soil within the boundaries of the site itself, in some instances in combination with limitations on the area permitted to be uncovered at any one given site or project. Often little or no serious effort has been made to insure that these measures were effective.

Fig. 1 Heavily Eroded Blue Clay Till Slope

The present thesis represents the results of a portion of a larger study having as its objective the investigation of expedient and economically feasible methods of stabilizing soils exposed on construction sites against rainfall erosion. The stabilization treatments are designed to be primarily of temporary character, i.e., to be superceded by permanent cover provided at or after the completion of the construction activities.

In the first portion of the study, conducted by Dr. Sidney Diamond and Dr. Mitsunori Kawamura, a rainfall simulation apparatus was designed and calibrated to yield a consistent design rainstorm for test purposes, and methods of preparing samples and determining the erosion loss after a given stabilizer treatment were established. The rainfall simulator erosion test is designed to establish the success of the stabilization treatment against the effect of raindrop impact only, and does not measure the response of the soil to erosion caused by running water on steep slopes.

In the first portion of the study it was established that reasonably low percentages of Portland cement or of hydrated lime were effective in stabilizing the two soils tested. In the present portion, similar results were obtained for four additional soils, constituting a wide spectrum of soil types; and a number of additional experiments were carried out designed to test (a) whether reduced compaction (less than that of the equivalent of Standard Proctor compaction) would be detrimental to the erosion protection attained, (b) whether the stabilizing agents would be effective if applied in slurry form at the soil surface rather than by mixing and compaction, (c) whether germination

and growth of grass would be compatible with the stabilization treatments, and (d) whether the projected costs of such treatments would be reasonable.

The four soils selected for study were obtained from various sites in Indiana and constituted the following assemblage: a till-derived silty clay material referred to as "Blue Clay Till" classified as an SC soil with about 20 percent clay and a PI of 10; another till-derived material referred to as "Tan Clay Till," classified as an SM soil, with much less clay, a PI of only 4, and a relatively high field density; a sandy soil referred to as "Glacial Outwash" soil, classified as a GM-GC soil; and a highly montmorillonitic clay soil referred to by the pedological soil series designation as "Romney" soil (B-horizon), with almost 50 percent clay, a PI of almost 40, and a CL-CH classification. Detailed characterizations of these soils are given in Table 1.

This thesis will first review the theories pertaining to erosion research and soil stabilization followed by a discussion of stabilization methods, laboratory preparation of samples, and rainfall testing. The results of these rainfall tests will be discussed in terms of erosion loss, and conclusions will be drawn as warranted.

LITERATURE REVIEW

Influence of Rainfall Impact on Soil Erosion

Erosion of soils by rainfall action usually occurs as a combination of two processes: raindrop impact and sheet washing. The impact of a rainfall drop splashes water and detached soil particles into the air. The accumulating rain will tend to run downslope and remove soil uniformly as it runs. However, vegetation and other obstacles tend to confine the erosive effects of the rain wash to the less resistant areas, creating rills, i.e., miniature stream channels. Mineral matter taken into solution when the rainwater comes into contact with the soil is another possible source of erosion, but this is of significance only with alkali or gypsum-bearing soils.

Young and Wiersma (1973) conducted research aimed at determining the relative importance of rainfall impact on soil erosion. Soils were tested at a nine percent slope to conform with the base slope of a preexisting soil loss equation. To differentiate between the effects of rainfall impact and sheet wash, the rain was applied either at full impact energy or at almost zero impact energy respectively, the energy being controlled by the height of raindrop fall with a constant intensity of rainfall application. To accomplish near zero energy, four layers of insect screen were placed above the soil sample, thus virtually preventing any rainfall impact. The conclusion drawn from their study is that rainfall impact is primarily responsible for soil erosion, an 89 percent reduction in rainfall impact energy resulting in a 92 percent reduction in soil loss at the same water application rate.

It must be kept in mind that actual rainfall erosion in a practical situation is a function of whether the soil is bare, covered with vegetation, or stabilized, and of the soil type, the inclination and length of the slope, and of the degree of compaction, if any.

History and Methods of Soil Stabilization

The necessary measures to accomplish soil stabilization are the addition of the stabilizing agents to the soil and the application of machinery to work the modified soil to the desired optimum condition. Various methods exist depending on the degree of mixing and compaction desired. Discussion here will be limited to lime and cement treatment methods normally employed in the field for the usual purpose of increasing the strength of the stabilized soil for use in highway subgrades, parking lots, etc.

Reviews of soil stabilization practice were presented by Herrin and Mitchell (1961) for lime treatment, and by Catton (1959) for cement treatment.

History

The earliest record of soil-cement stabilization in the United States followed a series of patents with the active involvement of the highway departments of the states of Iowa, Ohio and Texas in the early 1920's. South Carolina became involved approximately a decade later. Lime stabilization was used in the construction of the Appian Way by the Romans, but it was not until 1924 that a lime stabilized road was first built in America. However, neither lime nor cement stabilization

was used extensively until the Second World War. Many of the early lime stabilized roads were disappointing due to the lack of field control over mixing, compaction, and curing. Since then, the need for field and laboratory research has been evident, and such research has been extensively pursued. Among the areas of special interest were:

1. stabilizer-clay mineral reactions
2. physical soil properties, before and after modification
3. optimum construction procedures for various applications

Case histories have also served as an important phase in the understanding of soil stabilization, pointing out the weaknesses and limitations as well as the revelation of successful projects. Among the limitations of stabilization might be listed the following:

1. Climatic conditions - The warmer the temperature the better since the chemical reactions involved are slowed at low temperatures.
2. Permanence - The effects of lime stabilization in normal subgrades seems to be permanent except that a small increase in PI and a slight reduction in strength may occur after a considerable period of time.
3. Thickness of stabilized layer - both the depth of mechanical mixing and stabilizer penetration are limited.
4. Cracking of stablized layer.
5. Difficulty in field control.

An example of an effective case study is a recent report by Catanach and McDaniel (1971) concerning the stabilization of sand with cement for support of a conduit. The paper describes the use of a continuous type mixing plant to produce the soil-cement mix which was later placed in 12-inch lifts before compaction. The resulting foundation was of sufficient strength and minimized differential settlements.

Construction Methods

The methods available include compaction after mixing the soil with the stabilizer, various slurry application methods, and the "hole method," used only with lime.

Compaction After Mixing Method: Typically, the following steps are carried out for this method:

1. The soil is first scarified and pulverized.
2. The additive is uniformly applied in either dry or slurry form.
3. Water is added to achieve optimum moisture conditions for the compaction of the soil.
4. Mixing of lime, soil, and water is accomplished by use of a traveling mixer, stationary mixing plant, or a multiple pass rotary mixer.
5. Initial curing is allowed to occur while the soil loses its plasticity.
6. Final mixing,with water added if necessary.
7. Compaction, needed to take advantage of the hydration and cementation processes.

8. Final curing, while protecting against moisture loss. This can be achieved by covering the stabilized soil with a coating of bituminous material, moist soil, hay and sawdust, or waterproof paper.

This method, as described, would be entirely applicable for lime-soil stabilization. When the additive is cement, the initial curing and final mixing phases are unnecessary, and the time lapse before compaction is minimized to avoid a loss in final density.

Slurry Method: This consists simply of applying a lime or cement slurry to the soil which is either at field density or compacted density. The strength of the resulting product will not be as great as those developed from the previous method since the hydration process will not be advantageously used.

Hole Method: This method is intended for use with lime, and there are two variations:

1. The hole is drilled and the lime slurry is poured into it, seeping into the voids and in time migrating into the soil clods.
2. A tube is inserted into the clay, then the lime slurry is pressure injected into the voids and, as previously mentioned, migrates into the soil after a period of time.

Lime diffusion studies have shown that lime penetrates only for short distances; thus, this method has been shown to be relatively ineffective.

Soil Cement: Reactions and Physical Attributes of the Products

Theories of soil-cement stabilization help explain the physical ameliorative effects observed. The reactions will be discussed first followed by a compilation of the physical attributes of a cement stabilized soil.

Reactions

Unlike the situation with lime, discussions of the soil-cement reactions given by various authors are almost in agreement with each other.

Catton (1959) stated that cement hydration is the principal reaction, the grains of cement serving as a nucleus to which the fine soil particles adhere. Arman and Saifan (1967) supported the concept that hydration and cementation are responsible for the stabilizing effect of cement in soil.

Herzog and Mitchell (1963), Noble (1967), and Ingles and Metcalf (1973) agreed that the first reaction that takes place is an ion-exchange and the flocculation of soil particles creating "nuclei" of stabilized soil. As the cement stabilized soil ages, pozzolanic reactions and cement hydration create a skeletal structure and as a result of secondary cementation processes, the nuclei expand into each other. Noble included a third reaction, the crystallization of calcium hydroxide, $Ca(OH)_2$, which he considers is effective in cementing separate particles and floccules together.

Mitchell and El Jack (1965) performed electron microscope studies on three different soils at very high cement contents and found that the behavior for each of the soils is similar. Initially, separate

Portland cement grains were seen to be dispersed throughout the soil representing an initial fabric. Subsequently the cement hydrates and the resulting cement gel forms along the edges of clay particle aggregates. The soil grains appeared to break down and the cement gel expanded into the aggregate masses until the soil and the cement were indistinguishable as separate phases. The reactions observed are not likely to proceed to quite this extent in practical stabilization using more modest cement contents.

Physical Attributes

Soil properties change drastically when the soil is stabilized with cement.

Catton (1959) and the Portland Cement Association (1956) contributed information on the effect of small additions of cement as a permanent soil modifier. The plasticity index and the volume change both tend to decrease due to the formation of small conglomerate aggregates upon the addition of cement. Strength increases, the rate of increase being influenced by the curing period.

High cement contents are required to appreciably decrease the plasticity index and the volume change of soils with a high clay content. Soils with percent of clay sizes greater than 50 percent are difficult to mix and, therefore, impractical to stabilize with cement (Ingles and Metcalf, 1973). One way of handling such soils would be first to mix either cement or lime into the soil, thus modifying its properties. After the resulting reduction in PI, it would be easier to stabilize the modified soil with an additional treatment with cement followed by mixing and compaction.

Ingles and Metcalf (1973) and Noble (1967) show that strength, bearing capacity, and durability increase with an increase in cement content. Ingles and Metcalf also found that permeability in general decreased for an increase in cement content, except in clayey soils where an increase was observed. The tendency for a clay to swell was also reduced upon the addition of cement.

Davidson, Pitre, Mateos, and George (1962) performed an extensive series of tests to determine compaction and strength characteristics of cement treated soils. Their results show an increase of strength with increasing cement content and curing period.

Lightsey, Arman and Callihan (1970) concluded from their research on compaction of lime-soil mixtures that the optimum moisture content for compaction is not necessarily the moisture content that optimizes strength and durability. It was found that between two and four percent excess compaction moisture significantly improved the strength and durability. This was especially true when there was a delay in compaction.

Compaction is an important phase of stabilization, but compaction after cement hydration is ineffective. Arman and Saifan (1967) have investigated the effect of delayed compaction. They found that with a time delay of a few hours the compacted density of the stabilized soil is as much as 20 percent less than if the soil-cement is compacted immediately after mixing. As explained before, this is due to the formation of small conglomerate aggregates creating a larger void ratio and thus a decrease in the density. It was recommended that compaction should not be delayed beyond the initial setting time of the cement gel.

Lambe (summary, MIT Soil Stabilization Conference, 1952) mentions the limitations of soil-cement. Of concern are:

1. the requirement for moisture control during the curing period
2. the mixing problem when treating cohesive soils
3. tension cracks, which occur at high cement contents

George (1973) found that shrinkage stress is highly localized on the exposed surface of soil-cement slabs and decreases sharply with depth. Shrinkage cracking is more predominant in the more granular soils. Wang and Kremmydas (1970) used sodium chloride with soil-cement to reduce shrinkage. There was no strength reduction if the sodium chloride was powdered, but the coarser salt caused a decrease in strength, nullifying the merits of a high cement content.

Soil Lime: Reactions and Physical Attributes of the Products

Reactions

A number of reactions contributing to the amelioration of soil properties upon the incorporation with hydrated lime have been considered to occur, and some controversy has appeared in the literature.

Murray (1952) offered the explanation that modification of soil properties results from the alteration of forces and chemical bonds that unite the individual soil particles. The forces involved were theorized to be van der Waals forces which exist between molecules that have no localized electrical charges and polar forces which exist at a localized electric charge. The chemical bonds considered by Murray were classed as ionic bonds (caused by the electrostatic force that holds together oppositely charged ions), and covalent bonds (which exist when two atoms share an electron pair).

Flocculation of the clay particles has been theorized as contributing to stabilization, but flocculation alone does not stabilize the soil. Naturally flocculated soils occur and are not necessarily stable but become stable after responding to lime treatment. Flocculation is, therefore, an effect of stabilization treatment but not the mechanism responsible for the soil's improvement.

Clare and Cruchley (1957) asserted that flocculation occurs immediately after the introduction of lime, and after a period of curing the lime and the clay react to form a bonding of the particles by calcium silicates and/or aluminates having cementing properties.

Herrin and Mitchell (1961) considered ion exchange and cementation as the two reactions responsible for the improved soil properties and considered that carbonation is a reaction to be avoided. They considered that the base exchange reaction, where calcium cations from the lime replace the sodium of other monovalent cations previously present in the clay, and the crowding of additional lime-originated cations onto the clay surface, both increased the number of cations in the clay particles and were thought to be helpful in the stabilization.

Cation exchange was not considered a serious explanation for soil stabilization by Diamond and Kinter (1965) since many natural soils are already largely calcium saturated, but not stabilized. Rather, reaction of lime with silica-bearing soil particles creates a tough, water-insoluble gel of calcium silicate hydrate, thus cementing together soil particles; this is similar to the cementing action produced by the hydration of cement. Calcium aluminate hydrates are usually formed when aluminum-bearing minerals in the soil react with

the hydrated lime. Compaction is necessary for the required cementation to occur. Diamond and Kinter (1965) indicated that tetracalcium aluminate hydrate is formed rapidly by the reaction of Al(OH) groups at the edges of the clay particles, and that calcium oxide is absorbed on the faces of adjacent surfaces.

Carbonation of hydrated lime prior to its reaction with soil is a reaction that should be prevented from taking place since it results in weak cements, deterred soil reactions, and prevention of expected strength gains (Herrin and Mitchell, 1961; Diamond and Kinter, 1965). Hydrated lime should be protected in storage and in shipment to prevent the formation of calcium carbonate from the reaction of calcium hydroxide with carbon dioxide from the air.

Lime diffusion experiments have been undertaken to study the effect of lime penetration and migration into the soil clods, (Davidson, Demirel and Handy, 1965; Fohs and Kinter, 1972). Davidson et. al. found a linear relationship between the lime penetration thickness and the square root of time, provided that lime is constantly available to the system. They found that after a period of 28 days, a penetration of about 0.25 inches was realized. In this time period, the plastic limit was increased by 50 percent close to the surface (the point of lime-slurry application) but not at all at a depth of 0.6 inches. It was surmised that water was a means for diffusion of the lime. On the other hand, Fohs and Kinter (1972) considered lime diffusion as requiring compaction and not the movement of the lime solution. Lime-slurry migration was found to be a function of the percent slurry used. As the percent slurry was increased, the relative depth of migration increased, but only up to a depth of about 0.7 inches.

Physical Attributes

When a cohesive soil is mixed with water and lime and is allowed to cure for a period of time, aggregated masses of clay particles are formed and the soil becomes friable. This reaction occurs quicker when the soil is in a loose condition.

Most researchers are in agreement as to how the physical properties of the soil are changed (Herrin and Mitchell, 1961; Pietsh and Davidson, 1962; Diamond and Kinter, 1965; Townsend and Klym, 1966; Marks and Haliburton, 1972; Ingles and Metcalf, 1973; Diamond and Kawamura, 1974).

The effective grain size distribution is affected by the introduction of lime into the soil, the percentage retained on the larger sieves being greater than for the untreated soil. Flocculation of clay particles occurs and improves the soil texture, rendering the soil more workable.

The plasticity index decreases as the percent lime content increases. The liquid limit may increase, but a large increase in the plastic limit outweighs this. A maximum lime content exists beyond which the plasticity index will decrease no further.

The addition of lime restricts the volume change (swell) potential on wetting, and the swelling pressure is also reduced. The change in swell potential can be related to an increase in the shrinkage limit which occurs when the soil is mixed with lime.

Compaction variables are also affected by lime, the results being a decrease in dry density and an increase in the optimum moisture content. Lime-soil mixtures have greater compactibility than the untreated soils at higher moisture contents. Delayed compaction is not as critical with lime-soil mixes as it is with soil-cement combinations.

Ingles and Metcalf showed, for a heavy clay stabilized with 10 percent additive, a decrease in dry density of 10 percent for cement and one percent for lime after a six hour delay of compaction.

Acceleration of lime-clay reactions is possible with the use of small percentages of sodium chloride, as indicated by Marks and Haliburton (1972). It was found that using sodium chloride (in the amount of one to two percent of dry soil weight) in the water employed during preparation for compaction resulted in somewhat increased density, reduction in the optimum moisture content, and increased strength.

An increase in permeability is associated with flocculation, where larger pores between the flocs enable the fluid to flow more readily. Townsend and Klym (1966) show a marked increase in permeability for heavy clays, but erratic or no change for silty clay soils.

Both strength and durability are known to increase with the addition of lime, the affecting factors being lime content, type of soil, compactive effort and the time and type of curing.

The physical attributes discussed above can be related to the soil-lime reaction taking place. Diamond and Kinter (1965) relate these physical attributes to two distinct stages of reaction involved. In the first stage, the properties of the clay are improved but little strength is developed. During this stage the plasticity index decreases, the percent clay sizes decrease, compaction characteristics change as previously noted, and swell pressure and volume change decrease. The next stage represents the slow development of strength and durability.

LABORATORY STABILIZATION PROGRAM AND MATERIALS

Introduction

In order to evaluate the effectiveness of modest percentages of hydrated lime or Portland cement, laboratory methods had to be devised to simulate those methods used in the field. Two methods of incorporation of the additive have been used. In one of these, the soil and additive were mixed in the air-dry condition, brought to optimum moisture content, and compacted by a method which is similar to the Standard Proctor compaction procedure. The other method used was to prepare the soil in some definite compactive state and apply the stabilizer in slurry form evenly over the surface of the specimens.

The hydrated lime used in these experiments was a chemically pure (reagent grade) calcium hydroxide supplied by the Mallinckrodt Company. The Portland cement was a standard Type 1 cement supplied by Lone Star Industries.

Preparation of Specimens by Mixing and Compaction

The dry soil was mixed with the stabilizing additive at a standard level of one percent of additive per dry soil weight, previous studies having shown that effective erosion resistance can be realized even at such low additive contents. Water was then introduced to the system using a twin-shell solid liquid blender until the optimum moisture content was achieved. Then the soil sample was compacted to the desired density in a specially constructed mold. The specimens

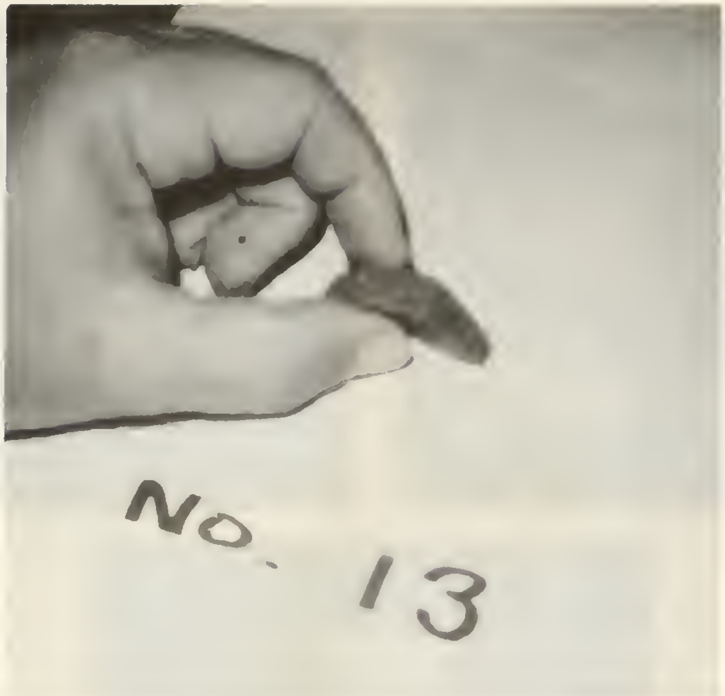
were then stored in a curing room (74°F and nearly 100 percent RH) for a predetermined length of time.

Preparation of Specimens Using Slurry Treatment

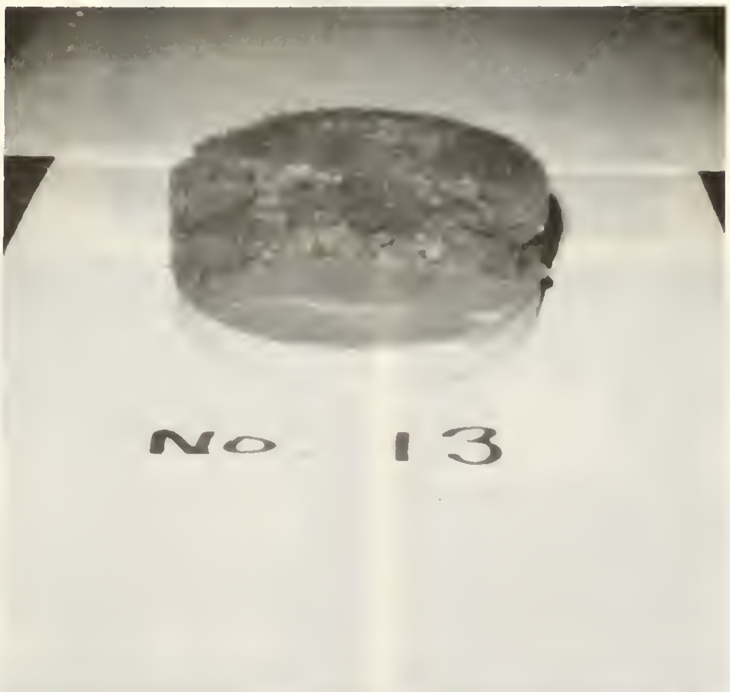
The dry soil was mixed with water in the twin-shell solid liquid blender until the desired optimum moisture content was attained. The soil was then densified at specified low compactive effort. The slurry, composed of deionized water mixed with either hydrated lime or Portland cement, was then carefully poured onto the surface of the soil sample. This process was followed by a period of storage in the curing room.

The level of compactive effort and the slurry concentration to be used were determined from a preliminary series of qualitative laboratory experiments, the results of which are tabulated in Appendix A. Samples compacted with 60 and with 10 blow compactive efforts and samples at approximately field density were investigated, and it was concluded that only the lower compactive efforts resulted in a reasonably satisfactory penetration of stabilizer, as shown in Figs. 2 and 3.

The optimum slurry concentration was determined by using slurries of a wide range of consistencies. It was found that the thinner slurry (of the order of 10 percent solids) penetrated well and that the additive stayed in suspension more readily in such slurries, and did not readily form a thick crust on the surface of the soil specimen.



(a)



(b)

Fig. 2 Photographs of Satisfactory Cement Slurry Stabilized Specimens
a) Thickness of stabilization achieved; b) Side view of specimen

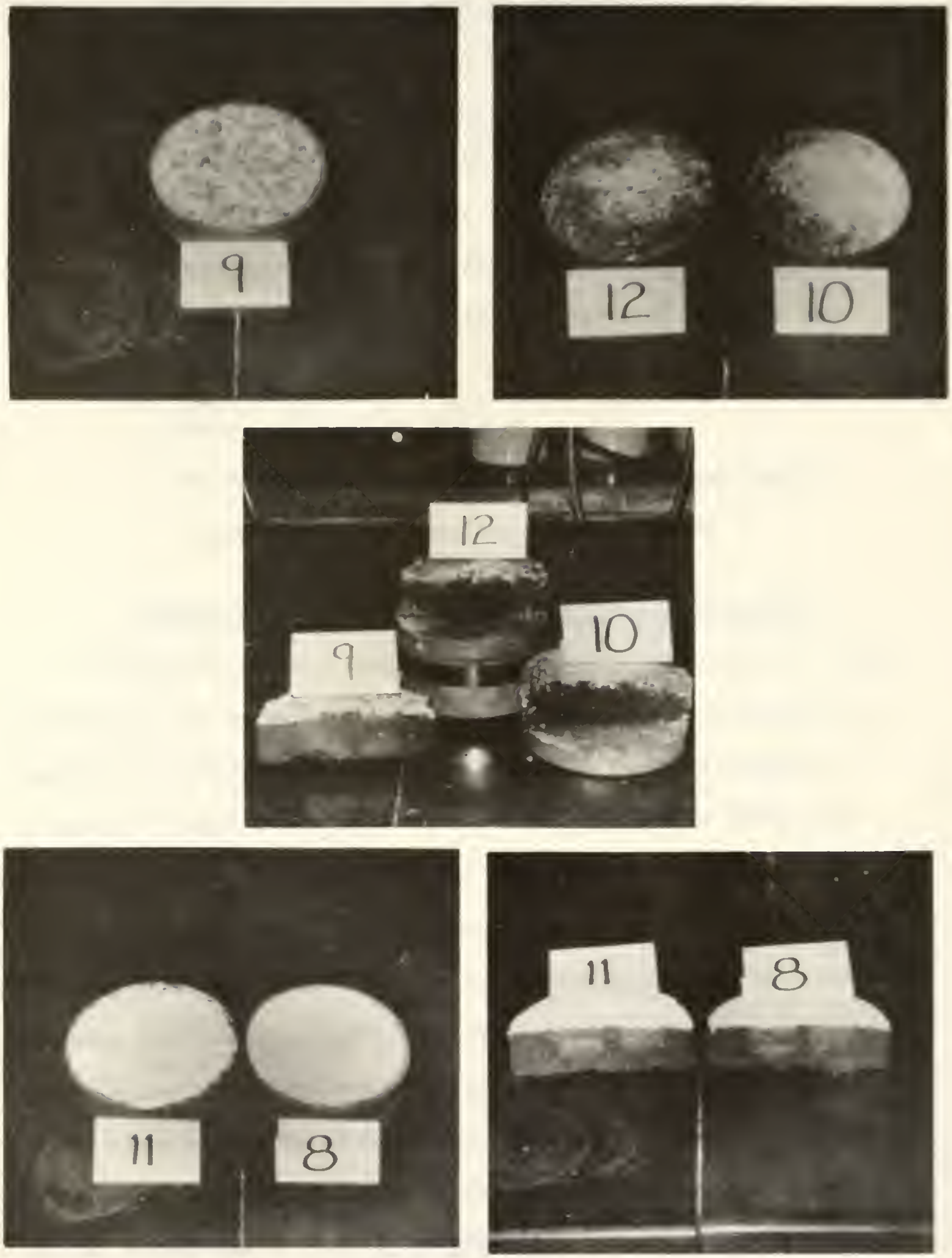


Fig. 3 Photographs of Qualitative Experiments with Various Compactive Efforts and Lime Slurry Concentrations (See Appendix A for details)

Properties of Soils Used in Experimental Work

The following laboratory tests were performed for a precise description of soil properties. The results are given in Table 1.

1. Specific gravity - ASTM Designation: D854-58
2. Particle size analysis - standard mechanical and hydrometer analysis, ASTM Designation: D422-63
3. Atterberg Limits - ASTM Designations: D423-66 and D424-59
4. X-ray diffraction analysis
5. Moisture-density relationship - (Standard Proctor method) ASTM Designation: D698-70 METHOD A

Compaction of Soils to Obtain a Variation in Density

The compaction mold used in the Standard Proctor test is 4-1/2 times larger in volume than the special mold used to prepare soil samples for rainfall testing (4.5 inches x 4 inches diameter vs. 1 inch x 4 inches diameter). Thus, a lower compactive effort was desired to compact the soil for testing at Standard Proctor density. It was found that the Standard Proctor hammer should be dropped 16 times to achieve standard density for a single layer by this method (Diamond and Kawamura, 1974). However, specimens prepared at lower densities were also desired. To facilitate this, the number of hammer blows needed to be decreased; however, this made it difficult to obtain an even distribution of density within the specimen. A lighter hammer was available, weighing 2.62 pounds (Fig. 4), and it was found that, with a drop height of 12 inches, 60 blows from this lighter compaction hammer achieved Standard Proctor density using

Table 1 Properties of Soils Tested

Tests \ Soils	Blue Clay Till	Tan Clay Till	Glacial Outwash	Romney
Specific Gravity	2.73	2.71	2.69	2.75
% Clay Size (< .002 mm)	20	5	3	48
Unified Soil Classification	SC	SM	GM-GC	CL-CH
Liquid Limit	23%	19%	21%	68%
Plastic Limit	13%	15%	16%	29%
Plasticity Index	10%	4%	5%	39%
Clay Minerals***	illite kaolinite chlorite montmorillonite	illite chlorite trace of kaolinite	illite chlorite vermiculite montmorillonite	montmorillonite trace of kaolinite
Standard Proctor Density	γ_d = 126.5 pcf	γ_d = 125 pcf	γ_d = 120 pcf	γ_d = 98.8 pcf
Field Dry Unit Weight	97.1 pcf*	103.4 pcf*	94.2 pcf*	72.8 pcf**

*using sand cone apparatus ASTM Designation: D1556-64

**using driven tube sampler

***X-ray diffraction results shown in Appendix B

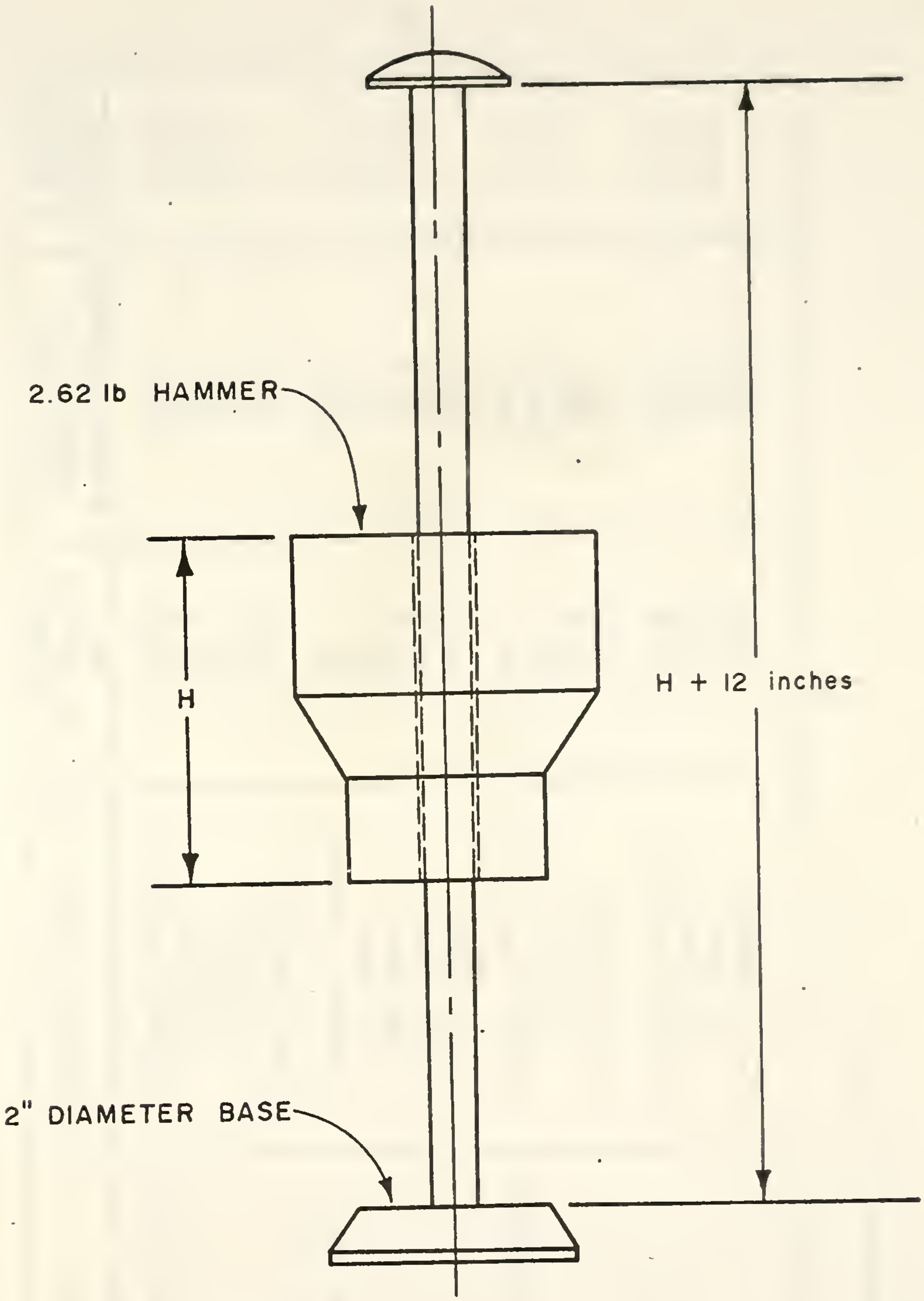


FIG. 4 2.62 lb COMPACTION HAMMER, WITH PERTINENT DIMENSIONS.

Table 2 Dry Unit Weights Produced by Variation in Compactive Effort

Soil	Compactive Effort	Maximum Dry Density pcf	Maximum Dry Density (% of Standard Proctor)	% Optimum Moisture Content
Blue Clay Till	Standard Proctor	126.5	100.0	10.0
	60 blows	127.8	101.0	10.0
	30 blows	123	97.2	12.0
	10 blows	116	91.7	14.2
	Field Density*	97.1	76.8	
Tan Clay Till	Standard Proctor	125	100.0	10.1
	60 blows	125	100.0	10.2
	30 blows	121.6	97.3	10.6
	10 blows	113.5	90.8	12.6
	Field Density*	103.4	82.7	
Glacial Outwash	Standard Proctor	120	100.0	12.3
	60 blows	120	100.0	12.3
	10 blows	110.2	91.8	13.6
	Field Density*	94.2	78.5	
Romney	Standard Proctor	98.8	100.0	22.0
	60 blows	98.8	100.0	22.0
	10 blows	78.3	79.3	33.5
	Field Density*	72.8	73.7	

*as measured in the field

550 grams of prepared soil for the Blue Clay Till, Tan Clay Till and Glacial Outwash soils and using 430 grams of prepared Romney soil in the special mold.

The compactive effort was then varied by reducing the number of blows. It was found that using 60, 30, and 10 compaction hammer blows approximately 100 percent, 96 percent, and 90 percent of Standard Proctor density, respectively, was attained. Field density was found to represent approximately 78 percent of standard density. To secure the equivalent of field density in the laboratory, the 2.62 pound compaction hammer was dropped from a reduced height of four inches, using eight blows. Table 2 shows the dry densities and moisture contents corresponding to the various compactive efforts for each of the four soils. The changes in moisture-density relationships as the compactive effort was varied for the soils tested are shown in Figs. 5 through 8.

Proportioning of Additive, Soil, and Water for Stabilization Mix

Proportioning of the components in the various mixes was governed by a set of equations developed for easy computation. The soil variables included the following:

X_d = weight of dry soil

X = weight of soil at storage moisture content

w_n = storage moisture content, being a function of soil type

w = optimum water content for a particular soil at a given compactive effort

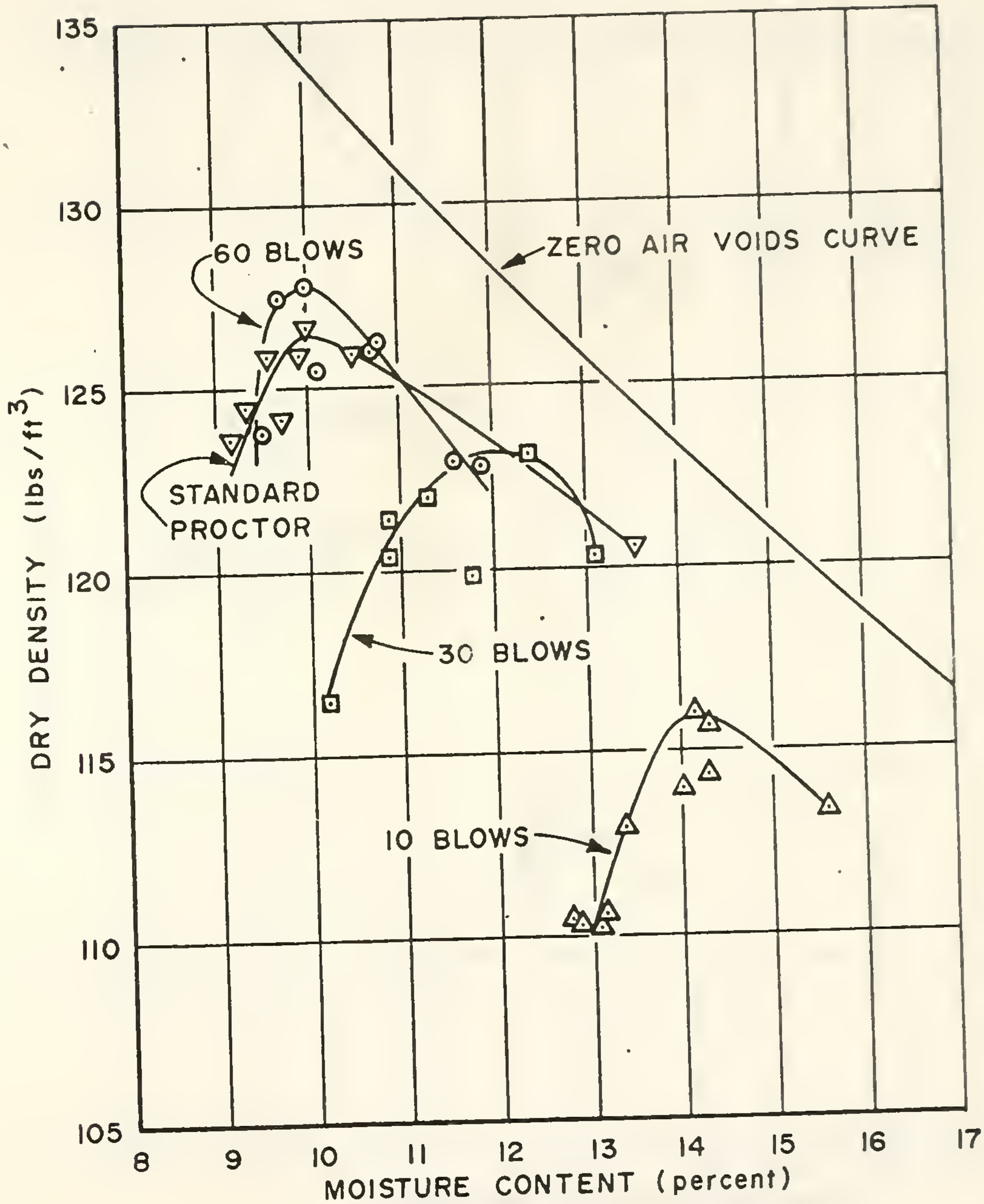


FIG. 5 MOISTURE-DENSITY RELATIONSHIPS OF BLUE CLAY TILL USING STANDARD PROCTOR, AND 2.62 lb HAMMER WITH 60, 30, AND 10 BLOWS.

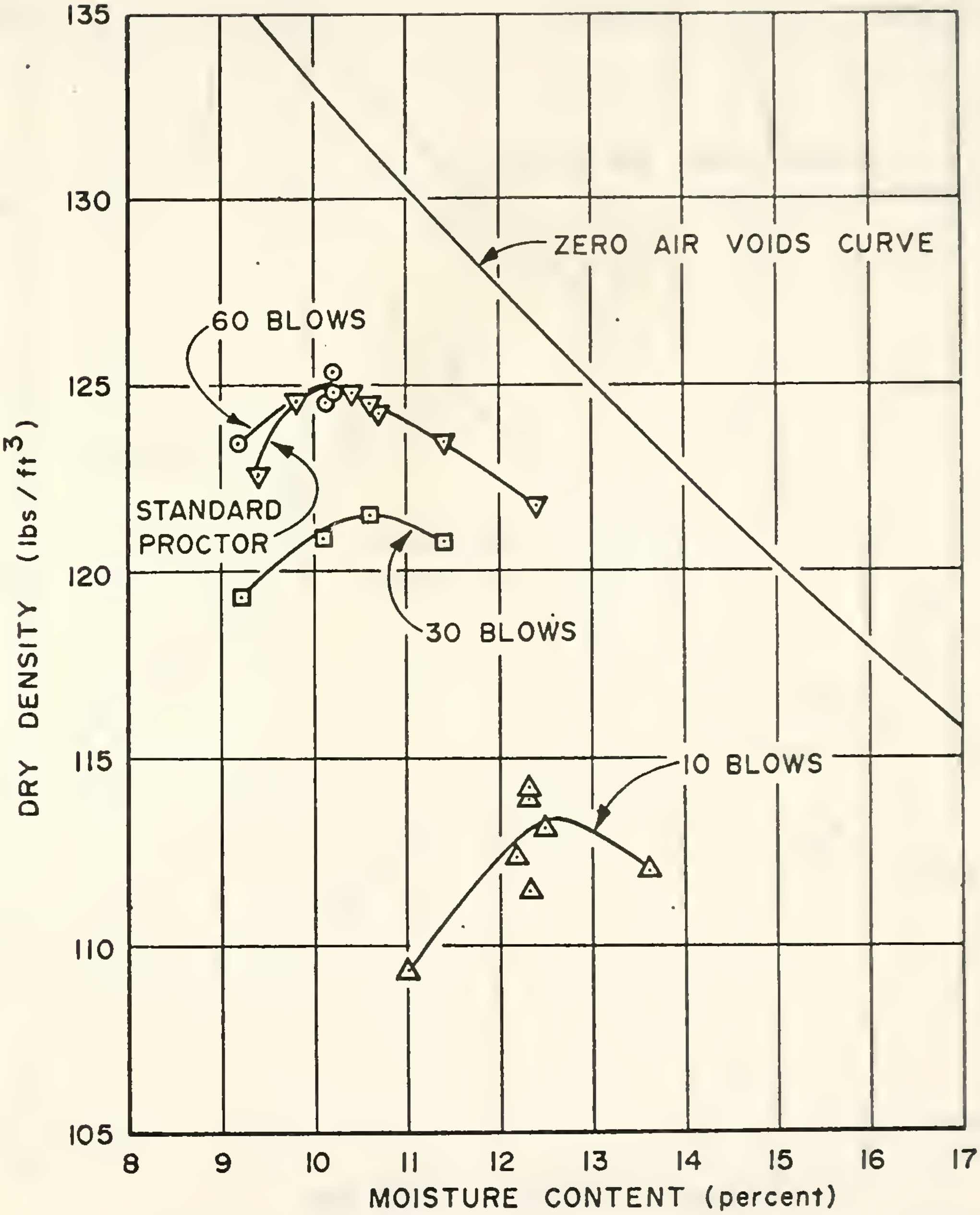


FIG. 6 MOISTURE-DENSITY RELATIONSHIPS FOR TAN CLAY TILL USING STANDARD PROCTOR AND 2.62 lb HAMMER WITH 60, 30, AND 10 BLOWS.

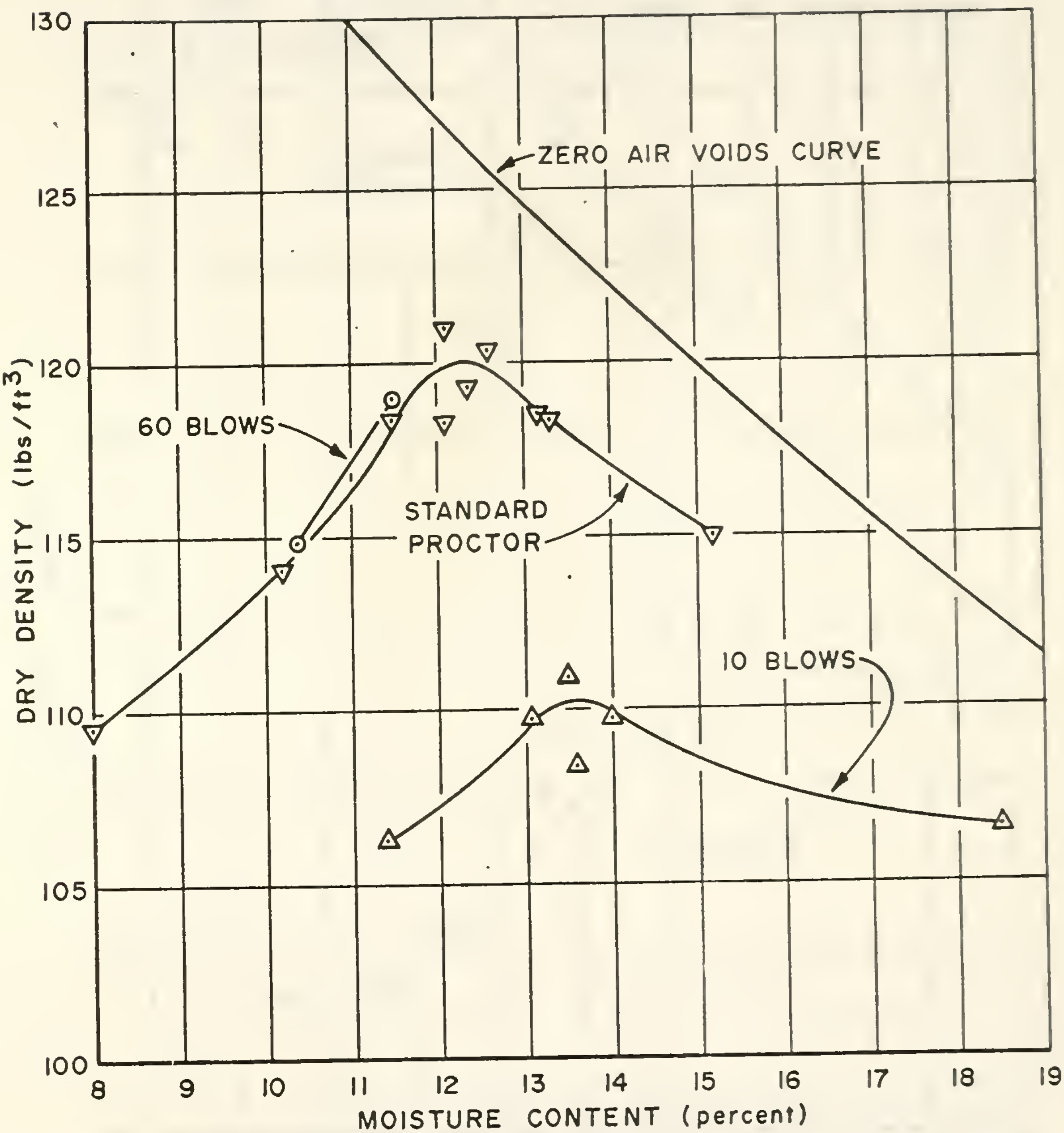


FIG. 7 MOISTURE-DENSITY RELATIONSHIPS FOR GLACIAL OUTWASH USING STANDARD PROCTOR, AND 2.62 lb HAMMER WITH 60 AND 10 BLOWS.

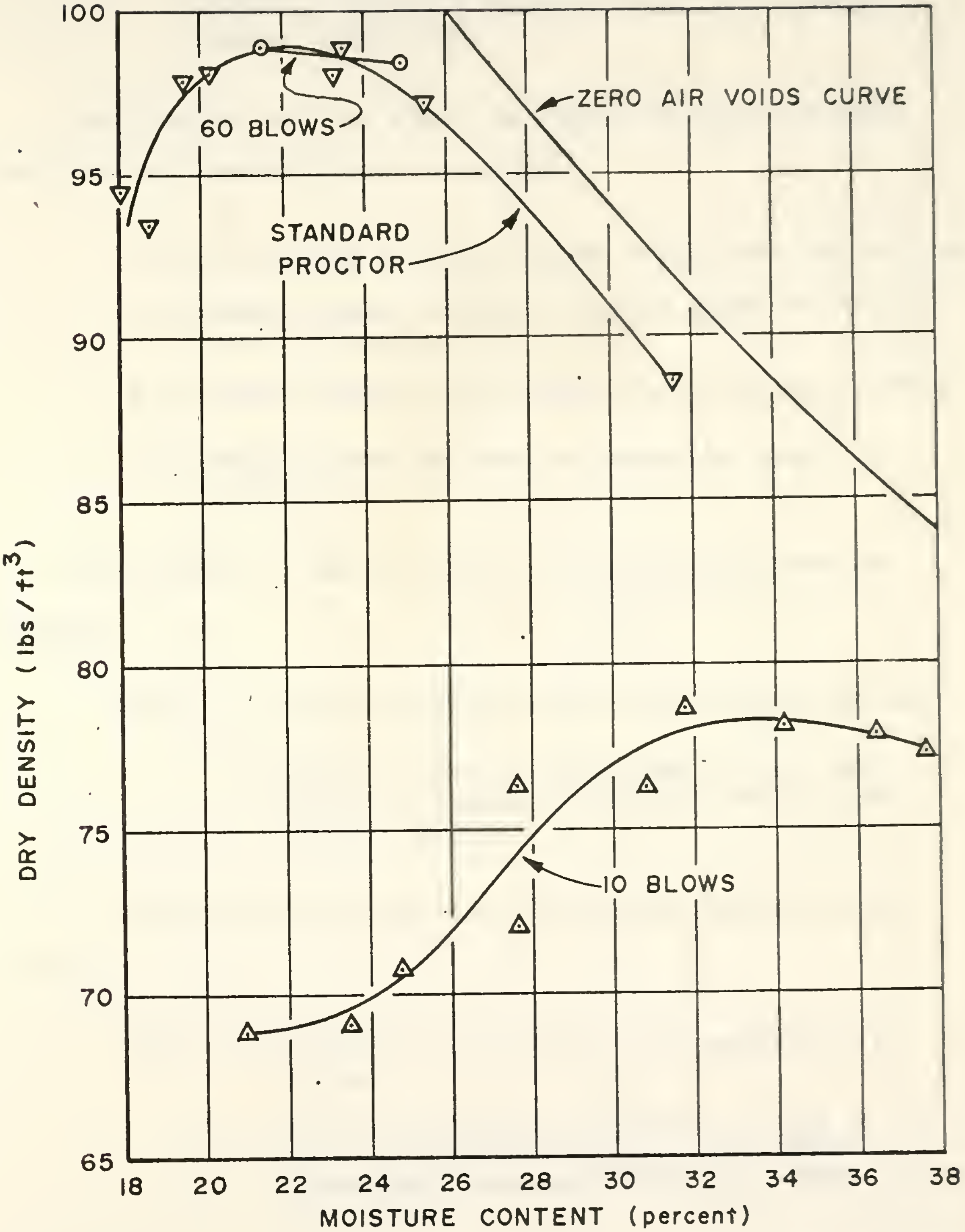


FIG. 8 MOISTURE DENSITY RELATIONSHIPS FOR ROMNEY USING STANDARD PROCTOR, AND 2.62 lb HAMMER WITH 60 AND 10 BLOWS.

T = total mix weight required for preparation of samples. This is determined by calculating the amount of stabilized soil needed to make three samples, and adding an additional amount to allow for a moisture content determination.

The following variables affect the amounts of water used (tap water was used unless otherwise specified):

W = total weight of water required in the stabilized soil mix

W_n = weight of water existing in a given amount of soil, X, taken from storage

W_w = weight of water to be added during the mixing operation

W_s = weight of deionized water to be used for slurry preparation

The variables for the soil-stabilizer mixing methods were as follows:

$100 \cdot w_A$ = percent additive desired in stabilized soil mix

A = weight of additive to be added to mix. This amount is based on a percentage ($100 \cdot w_A$) of dry soil weight.

The variables for the slurry application methods were as follows:

$100 \cdot S$ = percent slurry to be poured on compacted soil surface

A_s = weight of stabilizing additive to be used in the preparation of the slurry. This amount is based on a percentage ($100 \cdot S$) of total slurry weight.

The preceding definitions are used to derive equations for the dependent variables W_w, A, and X used in the calculations needed for the soil-stabilizer mix methods.

To find the equation for W_w, the previous definitions yield the identity $W_w = W - W_n$ where

$$W = X_d \cdot w = X\left[\frac{w}{1 + w_n}\right]$$

and

$$W_n = X_d \circ w_n = X\left[\frac{w_n}{1 + w_n}\right]$$

therefore,

$$W_w = W - W_b = X\left[\frac{w - w_n}{1 + w_n}\right] \qquad (1)$$

The identity for weight of stabilizing additive is

$$A = X\left[\frac{w_n}{1 + w_n}\right] \qquad (2)$$

The value of X depends on total weight, T, weight of water to be added to the mix, W_w, and the weight of stabilizing additive, A.

$$X = T - W_w - A$$

Then expanding the terms W_w and A as functions of X,

$$X = T - X\left[\frac{w - w_n}{1 + w_n}\right] - X\left[\frac{w_A}{1 + w_n}\right]$$

Rearranged and simplified,

$$T = X\ 1 + \left[\frac{w - w_n + w_A}{1 + w_n}\right]$$

or

$$X = \frac{T}{\left[1 + \frac{w - w_n + w_A}{1 + w_n}\right]} \tag{3}$$

For use with the slurry methods, the dependent variable is S. Since 100 · S is expressed as a percentage of total slurry weight, the following equation will hold true.

$$S = \frac{A_s}{\text{total slurry weight}} = \frac{A_s}{A_s + W_s} \tag{4}$$

This can also be expressed as

$$A_s = \left[\frac{S \cdot W_s}{1 - S}\right] \tag{4a}$$

Procedure for Preparation of Samples for Rainfall Testing

Soil brought in from the field was air-dried and then pulverized using a rotating drum, within which were placed rubber hose encased steel rods to help crush the soil without destroying the clay particles. The pulverized soil was then passed through a number 40 sieve, except that for the coarse Glacial Outwash soil a number 20 sieve was used so as to limit the granular content of the final soil-fraction to be tested. The soils were kept in plastic bags within storage bins until they were used for testing.

The equations for mix proportions were calculated as needed for each particular soil and moisture-density values.

A Patterson-Kelley twin-shell blending mixer was used to combine the elements of the pre-compaction mix. First the dry soil and additive

(if needed for the particular sample) were mixed for approximately 10 minutes. This was followed by another 20 minutes of blending with water being added to bring the mix to the optimum moisture content for compaction. These optimum moisture contents correspond to their respective compactive efforts and type of soil as shown in Table (2).

The 2.62 pound compaction hammer was used to compact the sample, of specified weight, into the special prelubricated molds (four inches in diameter and one inch in height). Each sample was then trimmed and placed in a plastic bag which was then sealed and placed in the curing room for a specified length of time.

A somewhat different procedure was followed to prepare specimens for slurry treatment. Here the soil was mixed only with water and then compacted to the specified low density. The sample was then turned upside down and the slurry was carefully poured over the sample surface until visible penetration of the solution had ceased. The slurry was made separately for each sample shortly before the pouring operation. It was found that 60 grams total weight of slurry was usually sufficient for the four inch diameter specimens. The samples were then bagged and left in the curing room for a predetermined period of time.

Generally, the curing periods chosen were 3, 7, and 28 days for lime stabilization, and 3 and 7 days for cement treatment.

<u>Erosion Testing Using Simulated Rainfall</u>

The rainfall simulation equipment used was designed with attention given to the rainfall intensity, size distribution, and fall velocity parameters of the desired rainstorm. The height in the laboratory

limited raindrop fall to 14 feet. This height is insufficient to enable all sizes of raindrops to reach terminal velocity, but it was found possible to design equipment to produce a rainstorm of the intensity desired where the applied impact energy was about 85 percent of natural rainfall impact energy. The raindrop formers were optimally spaced in triangular configurations to obtain an effectively uniform distribution of raindrops over the area exposed to rainfall. Intensity of rainfall was controlled by regulating the flow through the drop formers by means of a needle valve in the water supply line.

The equipment and the related soil specimen holders are shown in Figs. 9 and 10. The following major subassemblies refer to Fig. 9 and are described further by Diamond and Kawamura (1974).

1. Shutoff valve for rapid fill system (line I)
2. Flow control needle valve for controlling intensity of rainfall during test (line II)
3. Bleed valve for removal of trapped air from rainfall applicator box
4. Constant head tank
5. Water storage tank (three separate units provided)
6. Secondary water line filter
7. Primary water line filters
8. Main water supply shutoff valve
9. Water pump
10. Valve for controlling discharge from main storage tank to constant head tank
11. Rainfall applicator assembly
12. Specimen container assembly

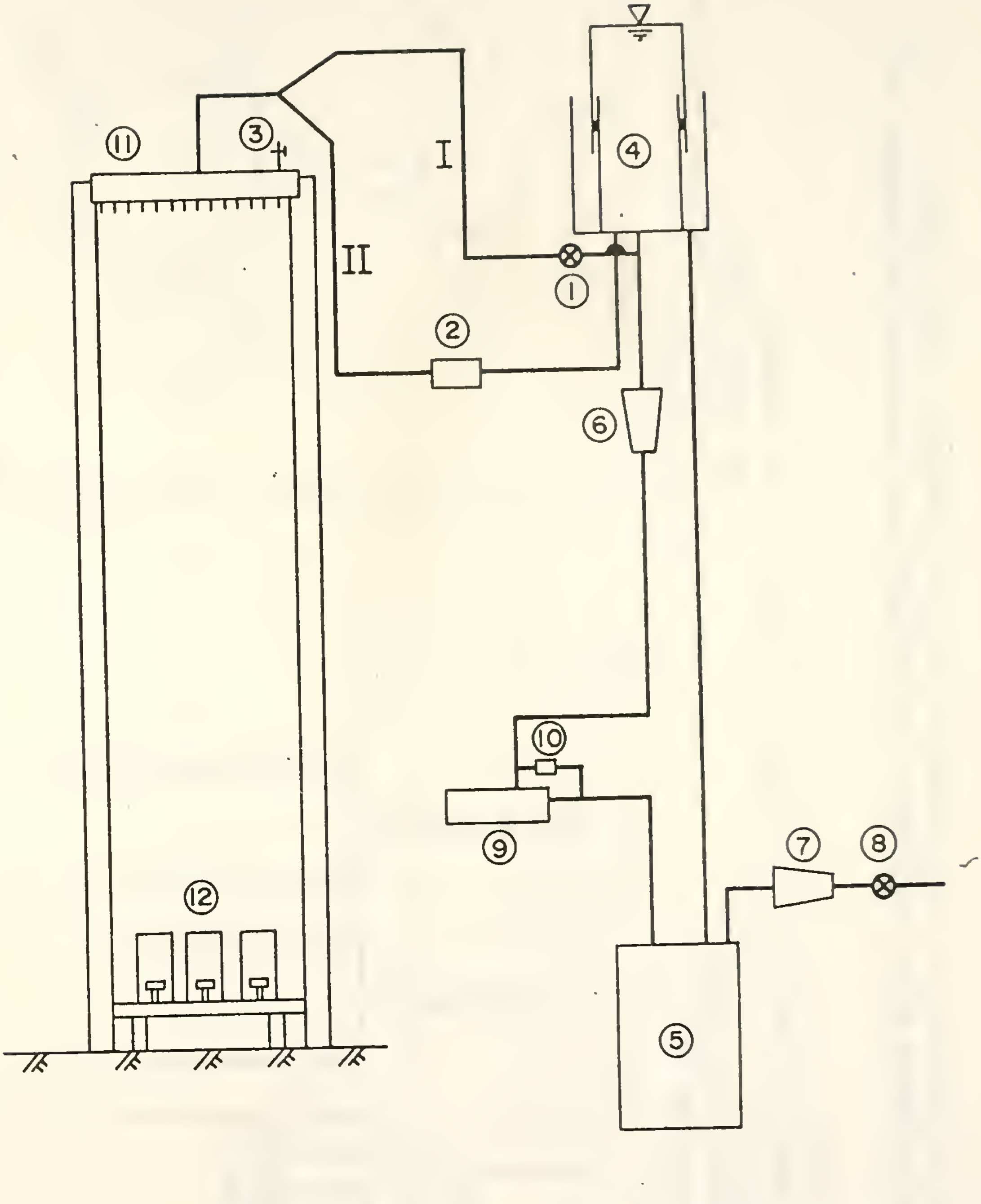
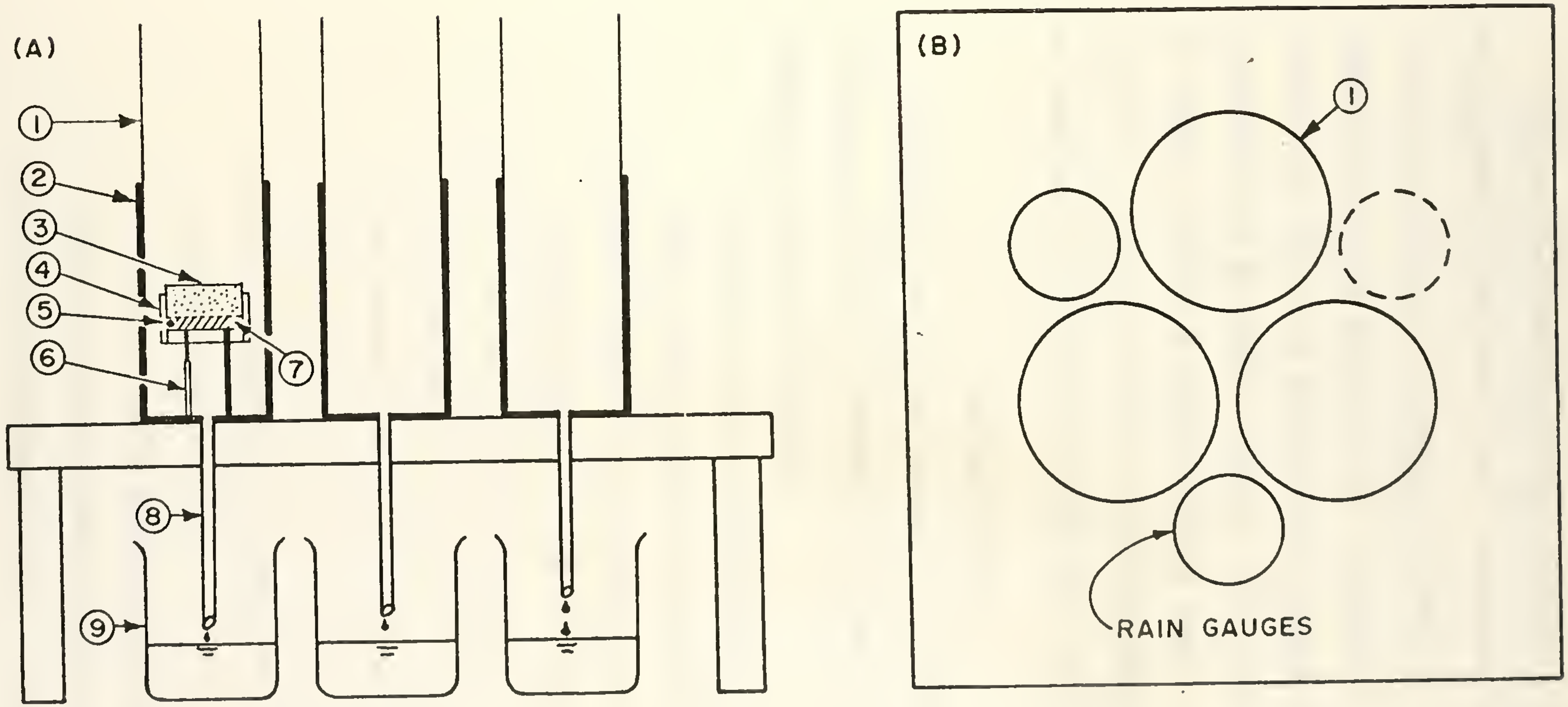


FIG. 9 FLOW CONTROL SYSTEM FOR RAINFALL SIMULATOR ASSEMBLY.



1. EXTENSION WALL
2. SAMPLE CONTAINER
3. SPECIMEN
4. OUTSIDE CYLINDER OF SPECIMEN HOLDER
5. "O" RING
6. SUPPORT
7. BASE OF SPECIMEN HOLDER
8. TYGON TUBE
9. BEAKER

FIG. 10 (A) SPECIMEN MOUNT ASSEMBLY AND SYSTEM FOR RECOVERY OF ERODED SOIL.
(B) POSITIONING OF TEST DEVICES AND RAIN GAUGES: PLAN VIEW.

The soil specimen size is four inches in diameter (small enough that the specimens can be free of soil transportation effects) and one inch in height (to allow for the expected erosion). The soil sample is supported at a five degree incline from the horizontal by the specimen holder (Fig. 10). This ensures free drainage and prevents water accumulation on the sample surface. The eroded soil is recovered in the beaker after being washed from the sample container through a tygon tube. It is the eroded soil which indicates the erodability of the specimen being presented in the final form of erosion/area (g/cm^2).

Testing Procedure

A brief outline of the procedure will be presented here. Reference can be made to Diamond and Kawamura (1974) for a complete commentary on testing procedure.

1. The water pump is switched on with the air bleed valve open to cycle water for approximately 10 minutes.
2. Both shutoff valve and needle valve are open so that the applicator box fills with water.
3. As soon as the applicator box is full of water, the air bleed valve is turned to the closed position.
4. The needle valve is closed immediately after and is then adjusted to give the desired rainfall intensity.
5. After the one-hour rainstorm of 3-1/4 inches intensity is completed, all of the water is removed from the applicator box by applying compressed air to blow out the residual water in any of the raindrop formers.
6. Valves and switches are then returned to their off positions.

7. Twenty-four hours later, this same procedure is repeated.
8. The soil sample is recovered, photographed, and a moisture content is determined.
9. The equipment (extension wall, sample container, and tygon tube) is cleaned of eroded soil; the soil is then collected in the beaker.
10. The eroded soil, in solution, collected from step 9 and from the two rainfalls is allowed to settle. The water is siphoned off and the soil is put into smaller beakers for a dry soil weight determination. This is separately done for all three samples, the weights being determined separately, and then averaged.

DISCUSSION OF RESULTS

The standard rainstorm has been applied many times to different specimens to yield over 90 individual results as tabulated in Appendix C and grouped under the four soil types used. The results represent the average weight of eroded soil per unit of specimen area (g/cm^2) for three replicates of the soils tested at various compactive efforts, stabilization methods, and curing periods. In order to put erosion losses into perspective, 1 g/cm^2 is equivalent to 45 tons of soil eroded per acre.

The erosion losses shown in the results relate to raindrop erosion under field conditions of flat terrain or short slopes of small inclination. The tests do not provide information on resistance to water running down steep slopes.

The discussion will consider five categories of results: unstabilized soil at various compactive efforts; conventional additive-soil mixing followed by standard compaction; conventional additive-soil mixing and reduced compaction; slurry application on untreated soil prepared under reduced compaction; and the ability of stabilized soils to grow grass.

Unstabilized Soil at Various Compactive Efforts

The evaluation of the effectiveness of a given stabilizing treatment will be made by comparing the erosion loss to that of the same soil

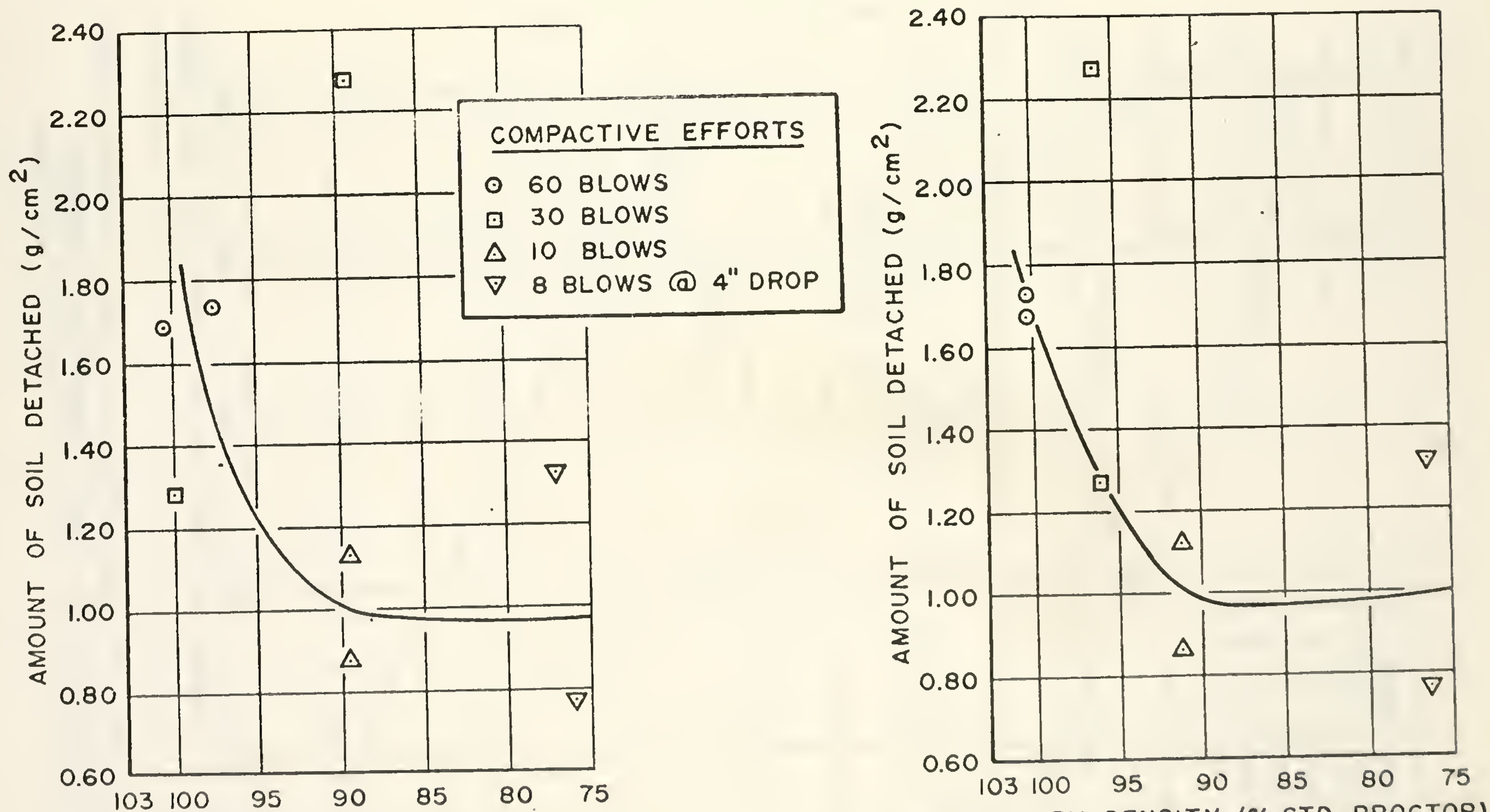
without stabilization treatment. Compaction has been varied as described earlier, and relationships involving the degree of compaction will be explored. Untreated soil at Standard Proctor density will serve as a base level against which the effects of stabilization treatment and compaction can be compared for evaluation of the relative success (in terms of a decrease in erosion per area). In order to be able to compare erosion results, the delay in rainfall testing after the preparation of untreated soil specimens was held to a minimum (on the order of one day) to keep any amount of strength increase with time at a constant level.

Under the standard rainstorm tests previously described, the erosion loss for untreated samples of density was found to vary considerably with density. The data indicate that the erosion loss is only partly dependent on the degree of compaction. Because of specimen to specimen variation, many samples would have to be tested at each compactive effort to show the details of the relationship clearly. A limited number of tests have been run in this fashion, the results of which indicate that, generally, the resistance to erosion increased with a decrease in dry density. This is opposite to the trend expected.

Diamond and Kawamura (1974) indicated in their report that unstabilized compacted soils (Crosby B and Grundite) lost on the order of 2 g/cm^2 of exposed soil by erosion due to raindrop impact in a standard test storm sequence as previously described. This statement is also true for the present results with Blue and Tan Clay Tills and the Glacial Outwash soil, the erosion per area ranging from 1 to 2-1/2 g/cm^2. Romney soil differed by being less susceptible to erosion, with the range being between 0.2 and 1 g/cm^2.

Of the four soils, Blue Clay Till has been experimented with the most. Untreated samples were prepared at four different compactive levels, as previously described, to show the relationship between erosion and level of compaction. Fig. 11 shows the results of numerous rainfall tests at the various compactive efforts. Fig. 11a provides data on erosion per unit area expressed as a function of measured dry density as measured independently for each specimen, expressed as a percentage of the Standard Proctor dry density. Fig. 11b is similar, but here erosion per unit area is plotted not against a dry density measured for each specimen, but rather against the value of the maximum dry density previously obtained in a compaction curve for that soil at that compactive effort (Figs. 5-8), expressed as a percentage of Standard Proctor density. For this plot, dry density of each specimen does not have to be determined but is assumed to be that of the value attained for that particular compactive effort. This dry density estimate will henceforth be referred to as "normalized" dry density. Examination of Fig. 11b shows that the trend is similar to that of Fig. 11a. Generally, the trend shows a decrease in soil loss with decreasing density, but the differences between the averages for repeated trials are large, and the precision of the relationship is poor for these untreated soils.

Fig. 12 shows the density-dependent soil erosion trends for Tan Clay Till, Glacial Outwash, and Romney soils. Each soil exhibits the previously mentioned trend of decreasing erosion with a reduction in compactive effort. It was originally expected that soils compacted at higher levels would erode less because of the higher shear strength



a) DRY DENSITY AS A PERCENTAGE OF STD. PROCTOR DENSITY

b) NORMALIZED DRY DENSITY (% STD. PROCTOR) BASED ON COMPACTIVE EFFORT

FIG. 11 EROSION LOSSES OF UNTREATED BLUE CLAY TILL AS A FUNCTION OF % OF STD. PROCTOR DRY DENSITY: a) BASED ON INDIVIDUAL DRY DENSITIES & b) SIMPLIFICATION BASED ON COMPACTIVE EFFORTS.

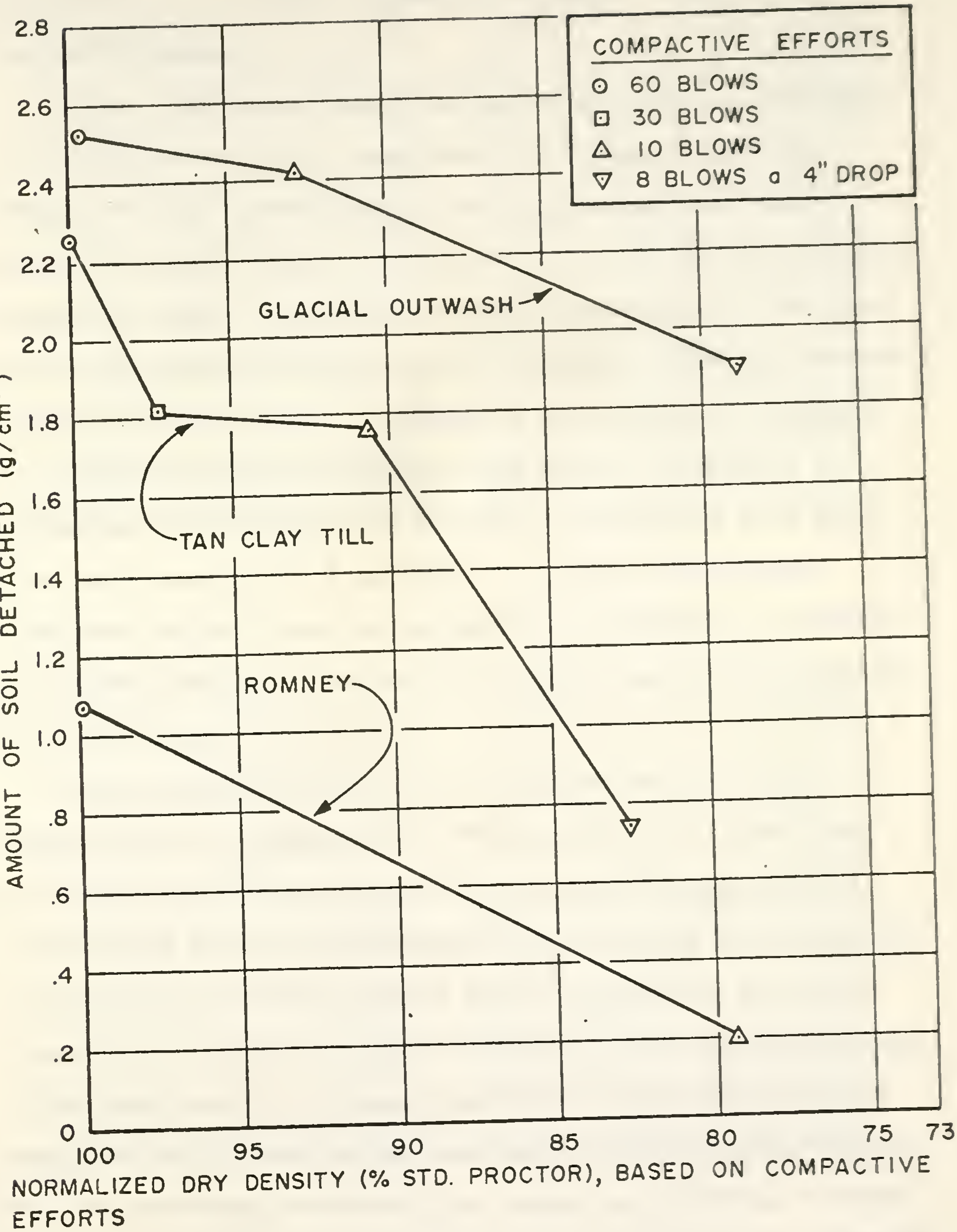
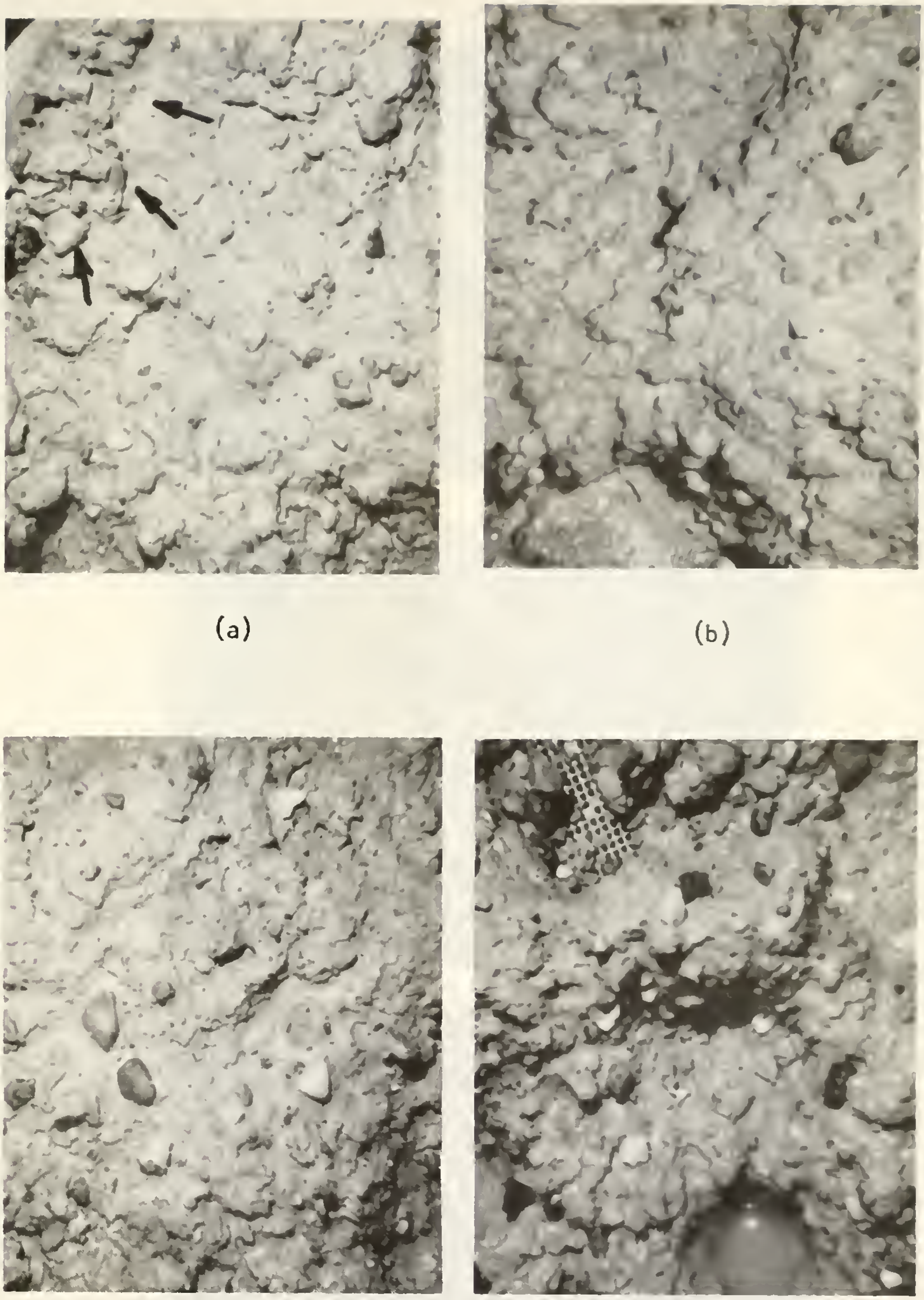


FIG. 12 EROSION LOSSES OF UNTREATED TAN CLAY TILL, GLACIAL OUTWASH, AND ROMNEY SOILS AS A FUNCTION OF NORMALIZED DRY DENSITY.

associated with the highly compacted soil samples. This does not seem to be the case.

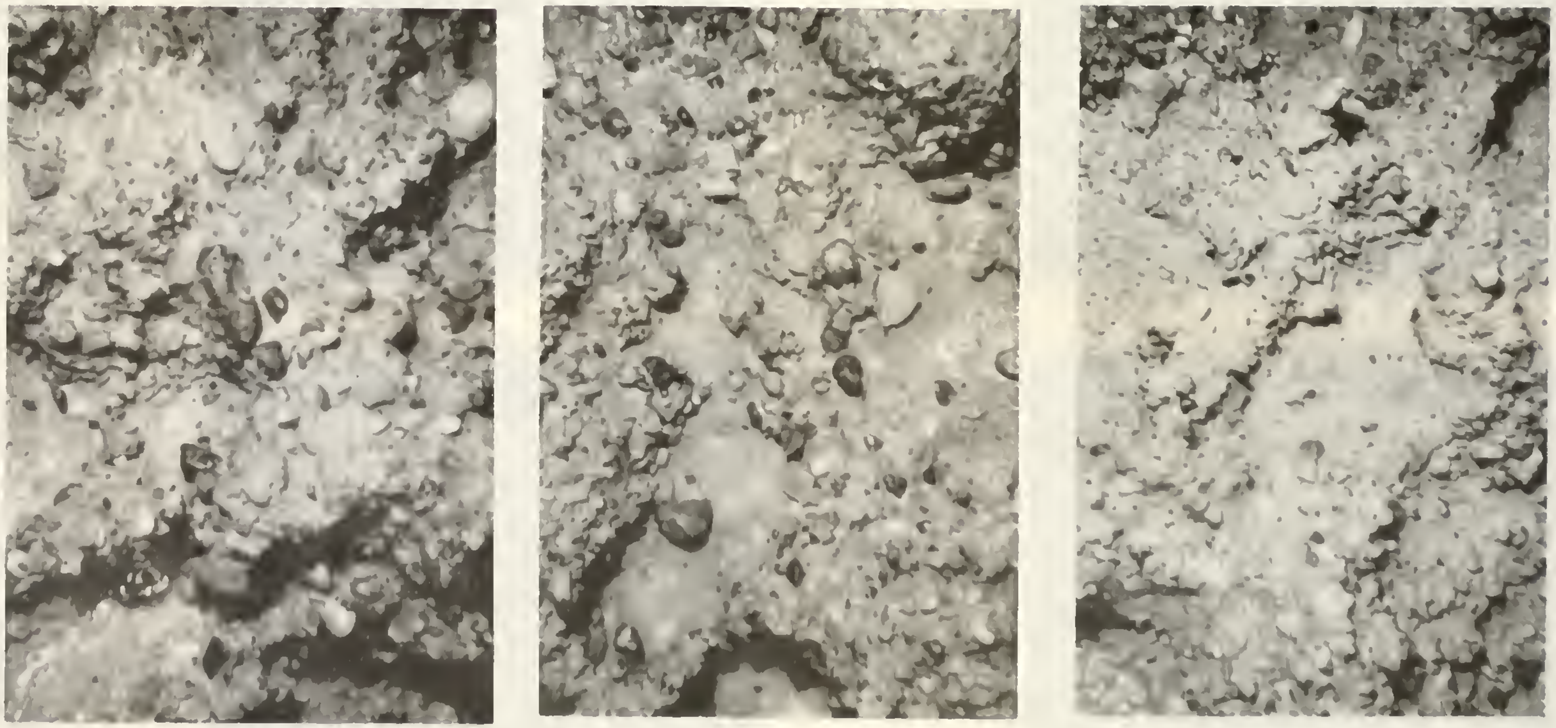
Wilson (1952) showed that a decrease in permeability accompanies the decrease in void ratio associated with increased compactive effort. The lower permeability at the higher compactive levels apparently influences the erosion by limiting the water flow vertically through the sample. Instead, the rainwater concentrates in the upper zone of the sample causing swelling and loosening of the soil specimen's exposed surface and edges. An example of such failure is outlined by the arrows in the upper left hand portion of Fig. 13a which is a macrophotograph of unstabilized Blue Clay Till compacted at 60 blows after the erosion test. In addition, it has been found by other researchers that soil swelling increases with increases in compactive effort, which fact might also partially explain the greater erosion at the higher compactive levels.

Macrophotographs (Figs. 13-16) of Blue and Tan Clay Tills, Glacial Outwash, and Romney soils at various compactive levels have been included to show the effect of the standard rainstorm applied. An observation from these photographs is that the sand and fine gravel-sized particles are visible and are free of any adhering clay. This disassociation is due to the dispersive action of the raindrops applied at high impact energy. A second observation is that among the soils tested, the soils containing more sand and fine gravel-sized particles have less resistance to erosion, i.e., Romney soil, which has a highly aggregated structure of clay particles (these aggregate masses being evident in Fig. (16) and is virtually free of fine gravel-sized



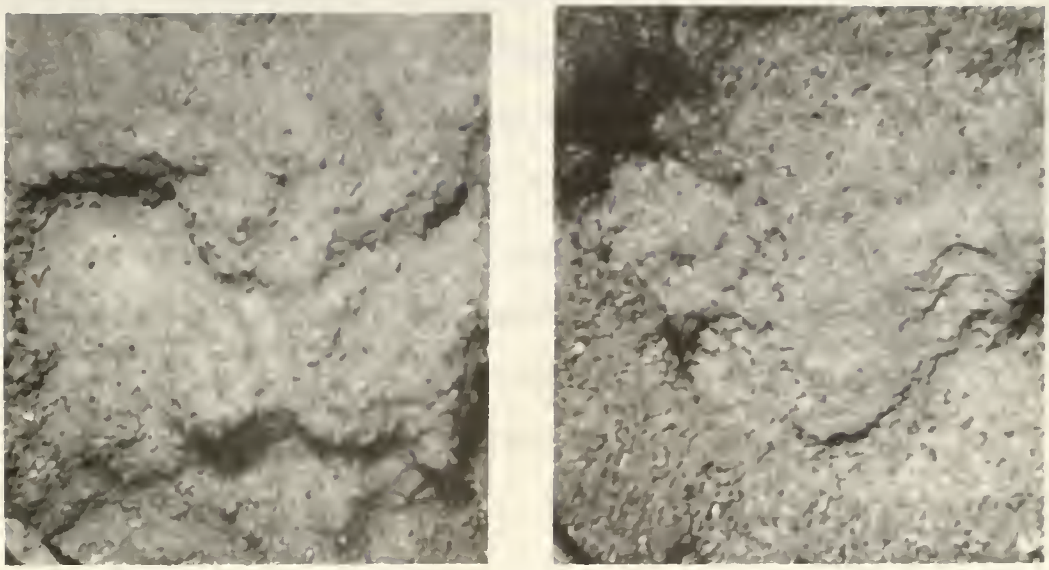
(a) (b) (c) (d)

Fig. 13 Untreated Blue Clay Till at Various Compactive Efforts
(a) 60 blows (b) 30 blows (c) 10 blows (d) 8 blows @ 4" drop



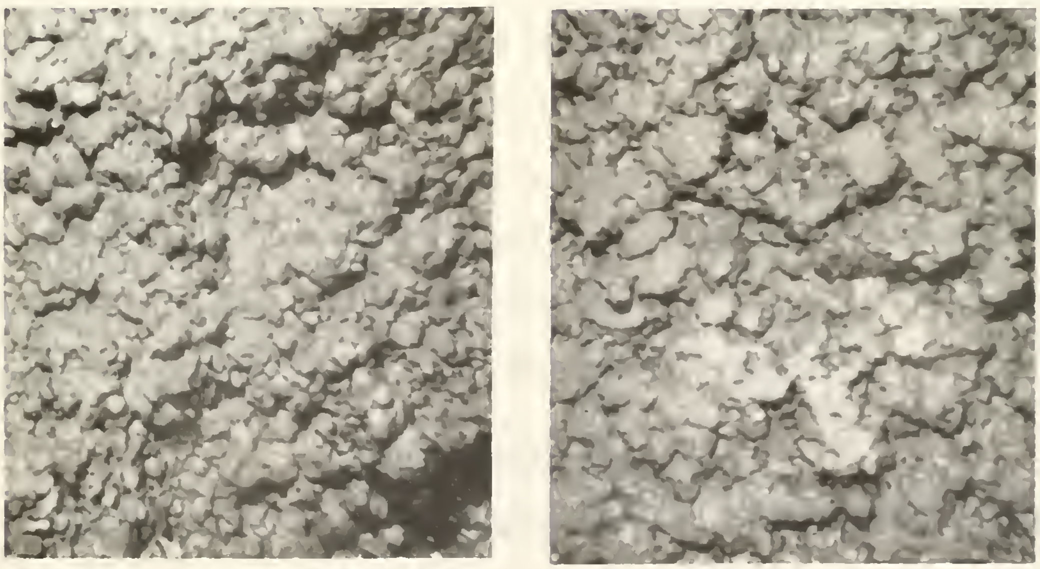
(a) (b) (c)

Fig. 14 Untreated Tan Clay Till at Various Compactive Efforts
(a) 60 blows (b) 30 blows (c) 10 blows



(a) (b)

Fig. 15 Untreated Glacial Outwash Soil at Various Compactive Efforts
(a) 60 blows (b) 10 blows



(a) (b)

Fig. 16 Untreated Romney Soil at Various Compactive Efforts
(a) 60 blows (b) 10 blows

particles, resisted erosion far better than Glacial Outwash soil which is predominantly made up of sand and fine gravel-sized particles. As mentioned earlier, the effect of variation in compaction for these soils was similar to that observed with Blue Clay Till except that the trend to increasing erosion resistance with lower compactive efforts continued to the lowest efforts used. The photographs of Figs. 13-16 will help orient the reader when comparing the results of these untreated samples with the stabilized samples to be discussed subsequently.

Conventional Additive-Soil Mixing Followed by Standard Compaction

Laboratory soil stabilization involving the addition of hydrated lime or Portland cement in the amount of one percent of dry soil weight has resulted in an appreciable improvement of erosion resistance. All of the four soils at Standard Proctor density (60 blows of a 2.62 pound hammer) have reacted favorably with the stabilizing additives to reduce erosion significantly: by a factor of 10 for Blue and Tan Clay Tills and Glacial Outwash soil, and by at least a factor of two for Romney soil. Since the ameliorative trends are different for lime and cement treatments, they will be discussed separately.

Portland Cement Treatment

Cement treated soils react quickly, with a decrease in erosion of more than 10 fold in three days of curing, and of a factor of 35 or more after seven days of curing. Romney soil, a heavy montmorillonitic clay, is an exception to the usual trend, the reduction of erosion being somewhat less marked. Curing periods greater than seven days

for Romney soil would result in only minimal increases of resistance to erosion; therefore, if the resistance desired is not attained by seven curing days, an increase in cement content would be warranted. Romney soil at reduced compactive effort was tested with three percent cement and was successfully stabilized, as will be discussed subsequently. Representative macrophotographs, shown in Figs. 17 and 18, exhibit the typical appearance of the specimens after having been subjected to the test rainstorms previously described. It can be seen that the degree of erosion in Blue Clay Till (Figs. 17e and f) is basically the same for curing periods of three and seven days. This trend is also true for Glacial Outwash soil demonstrating that for these two soils cement stabilization greatly reduces erosion and attains this marked reduction in a matter of a few days. Plots of erosion versus curing time are shown in Figs. 19a, 21a, 23a and 25a, all of which show excellent improvement for all soils tested at Standard Proctor density with one percent cement added in the mixing stage. The erosion loss in Tan Clay Till more than halved from three to seven days of curing with the overall soil loss less than one-hundredth of untreated specimens. Because of the high clay content of Romney soil, a larger amount of cement is needed to react with sufficient clay particles to produce erosion resistances resembling the three other soils.

Hydrated Lime Treatment

Lime treated soils are generally less erosion resistant than cement treated soils at short curing periods using the same percentage of stabilizing additive. The relatively long curing period required to attain maximum resistance to erosion tends to make lime stabilization

(a)

(b)

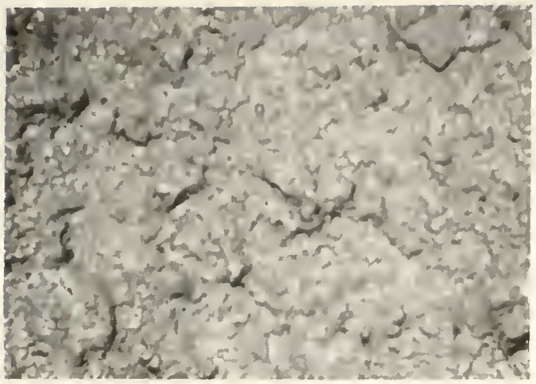
(c)

(d)

(e)

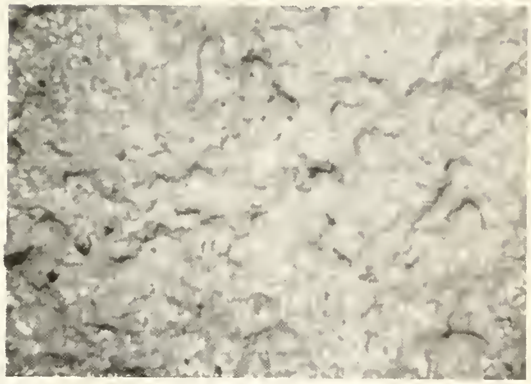
(f)

Fig. 17 Untreated and Treated Blue Clay Till at Standard Proctor Density with Variations in Stabilizer and Curing Period (a) Untreated (b) 1% lime at 3 curing days (c) 1% lime at 7 curing days (d) 1% lime at 28 curing days (e) 1% cement at 3 curing days (f) 1% cement at 7 curing days

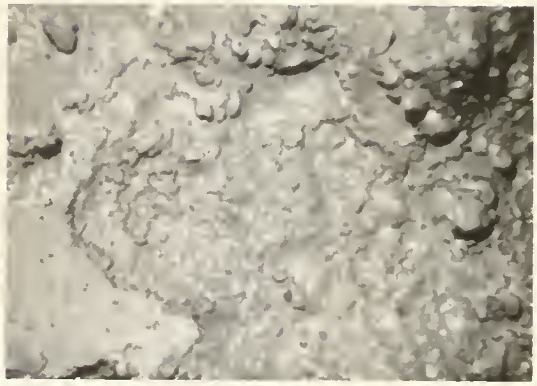


(a)

(b)



(c)



(d)

(e)

Fig. 18 Treated Tan Clay Till at Standard Proctor Density with Variations in Stabilizer and Curing Period (a) 1% cement at 3 curing days (b) 1% cement at 7 curing days (c) 1% lime at 3 curing days (d) 1% lime at 7 curing days (e) 1% lime at 28 curing days

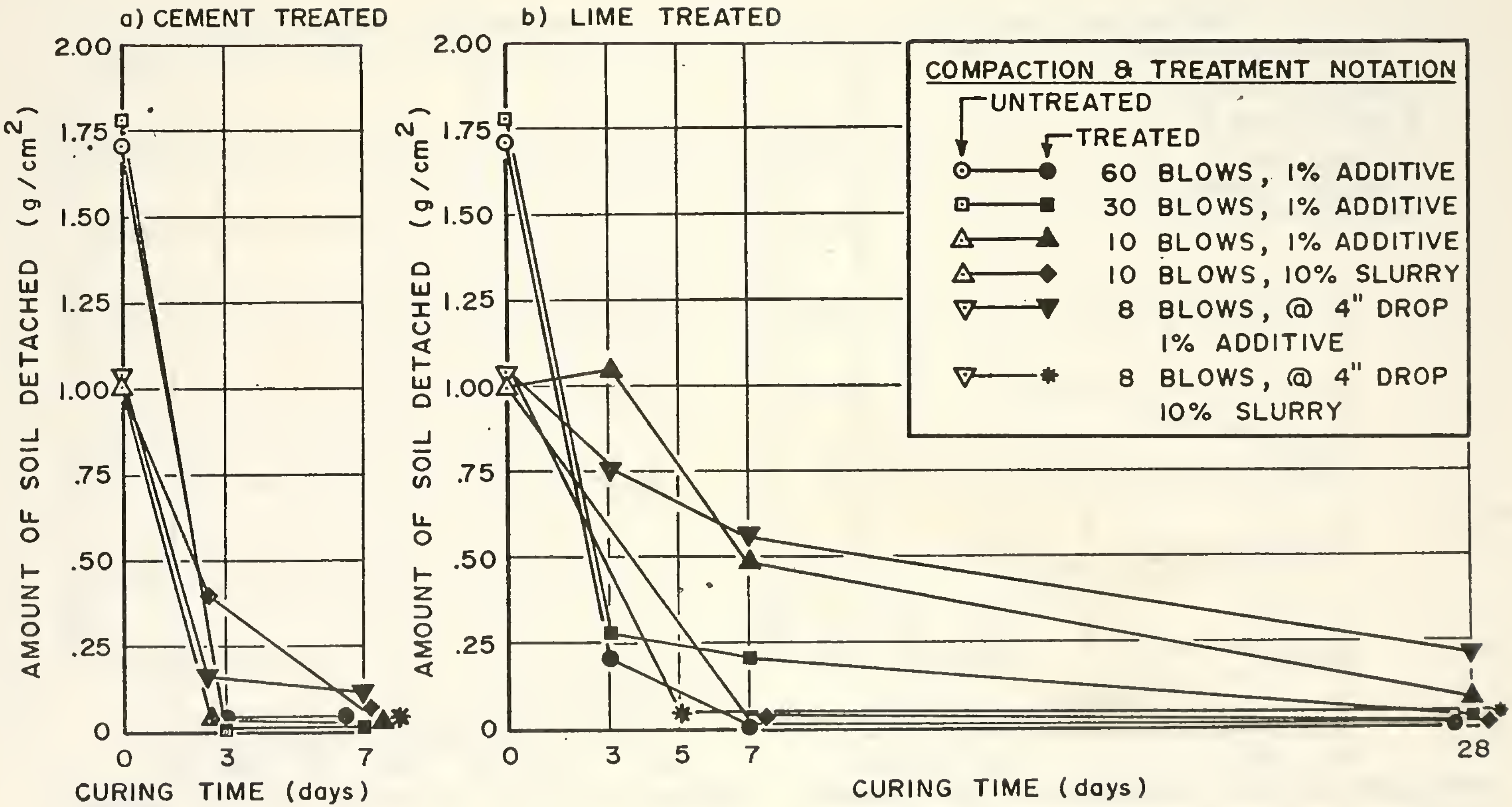


FIG. 19 AMOUNT OF SOIL DETACHED VS CURING TIME, WITH A VARIATION IN STABILIZING TREATMENT AND COMPACTIVE EFFORT: BLUE CLAY TILL.

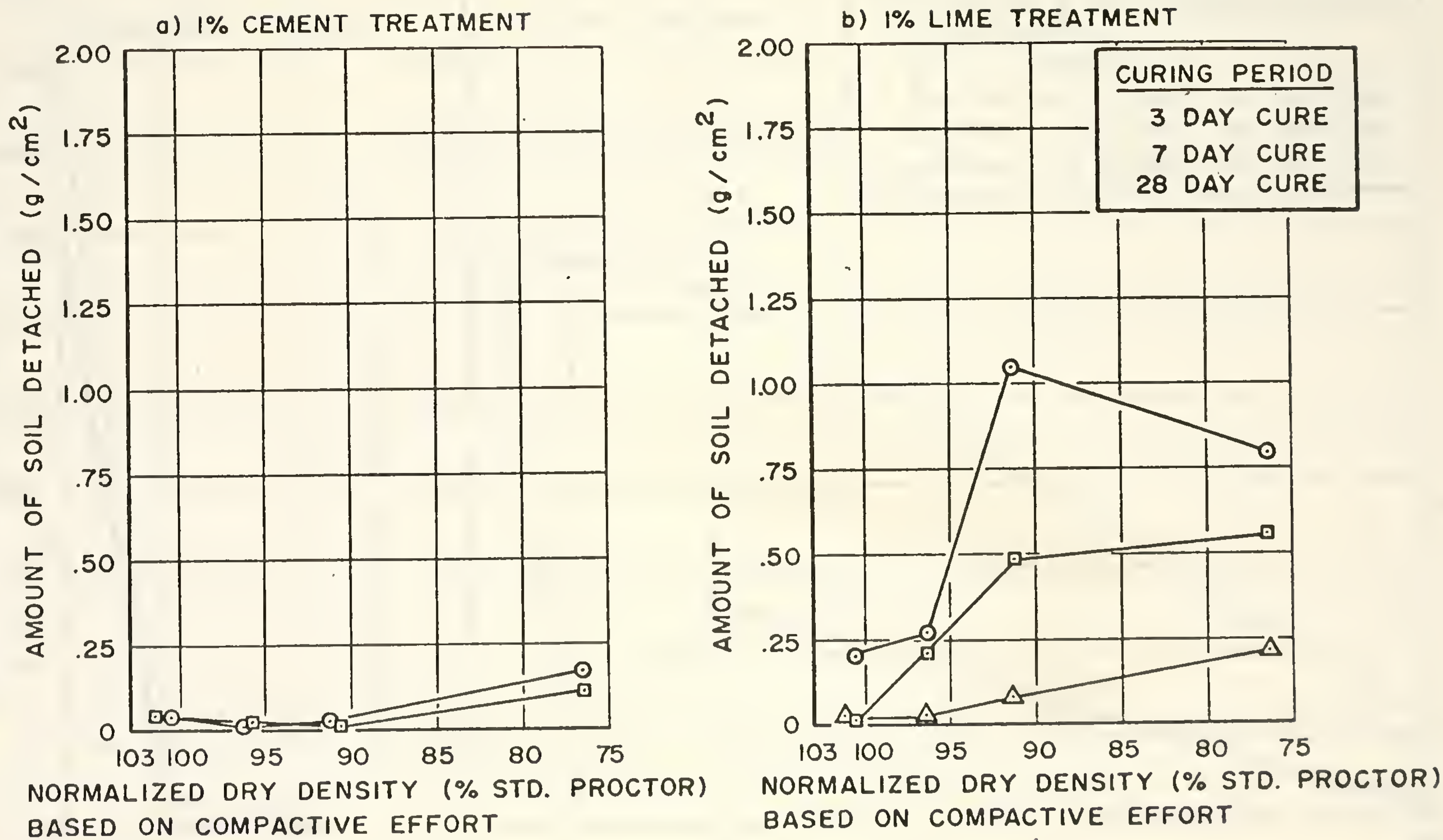


FIG. 20 EROSION LOSSES OF BLUE CLAY TILL AS A FUNCTION OF STABILIZER, NORMALIZED DRY DENSITY AND CURING PERIOD.

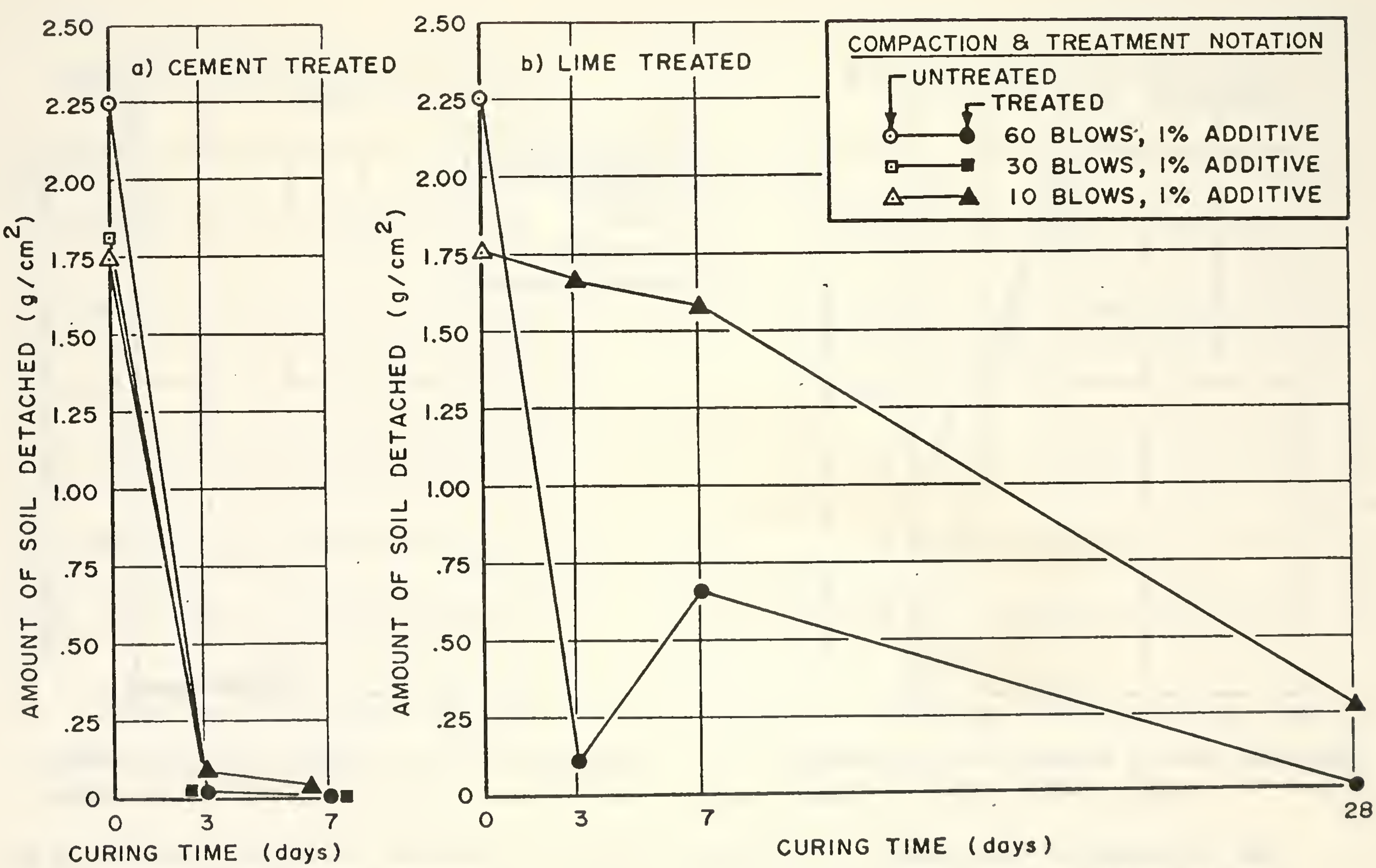


FIG. 21 AMOUNT OF SOIL DETACHED VS CURING TIME, WITH A VARIATION IN STABILIZING TREATMENT AND COMPACTIVE EFFORT: TAN CLAY TILL.

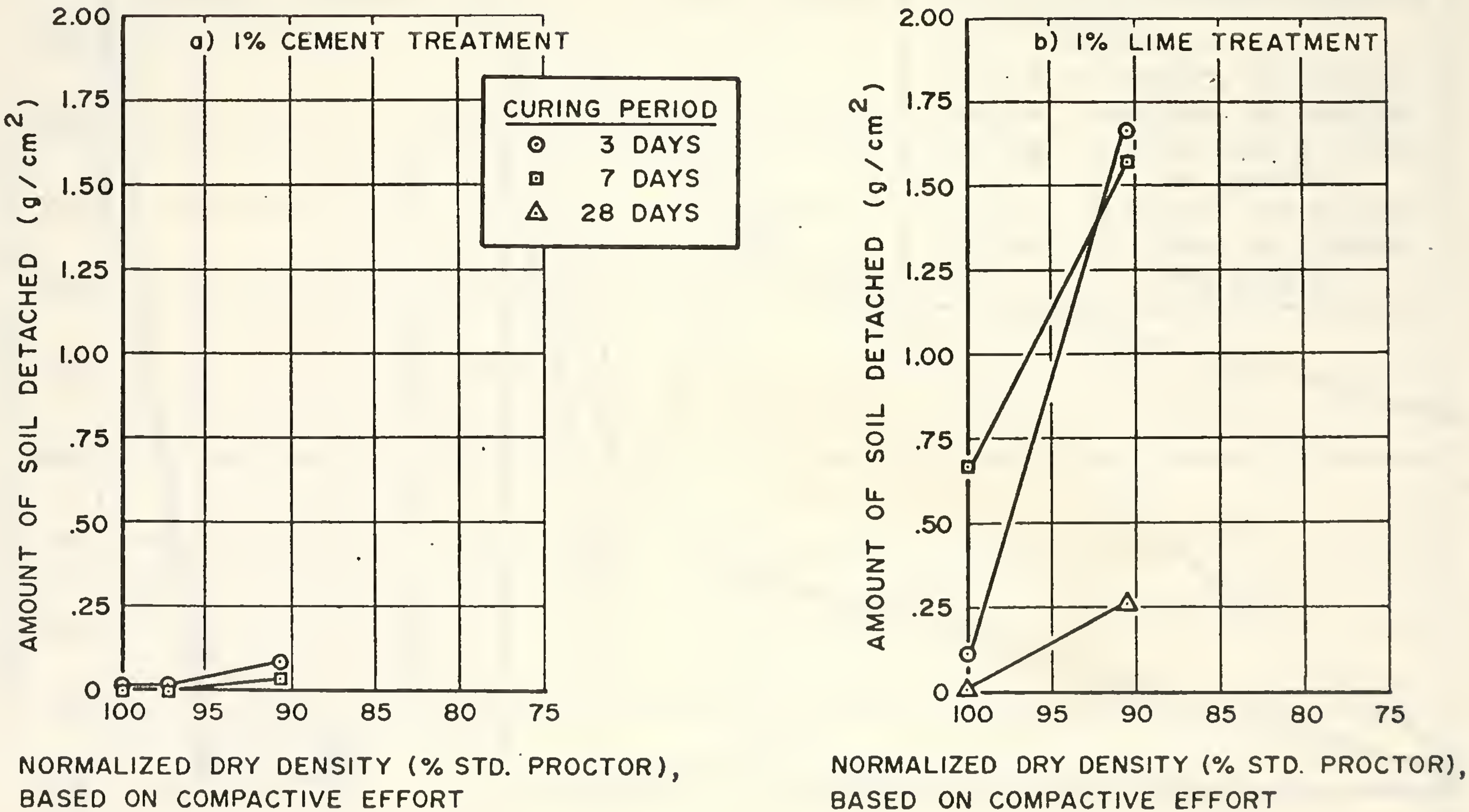


FIG. 22 EROSION LOSSES OF TAN CLAY TILL AS A FUNCTION OF STABILIZER, NORMALIZED DRY DENSITY AND CURING PERIOD.

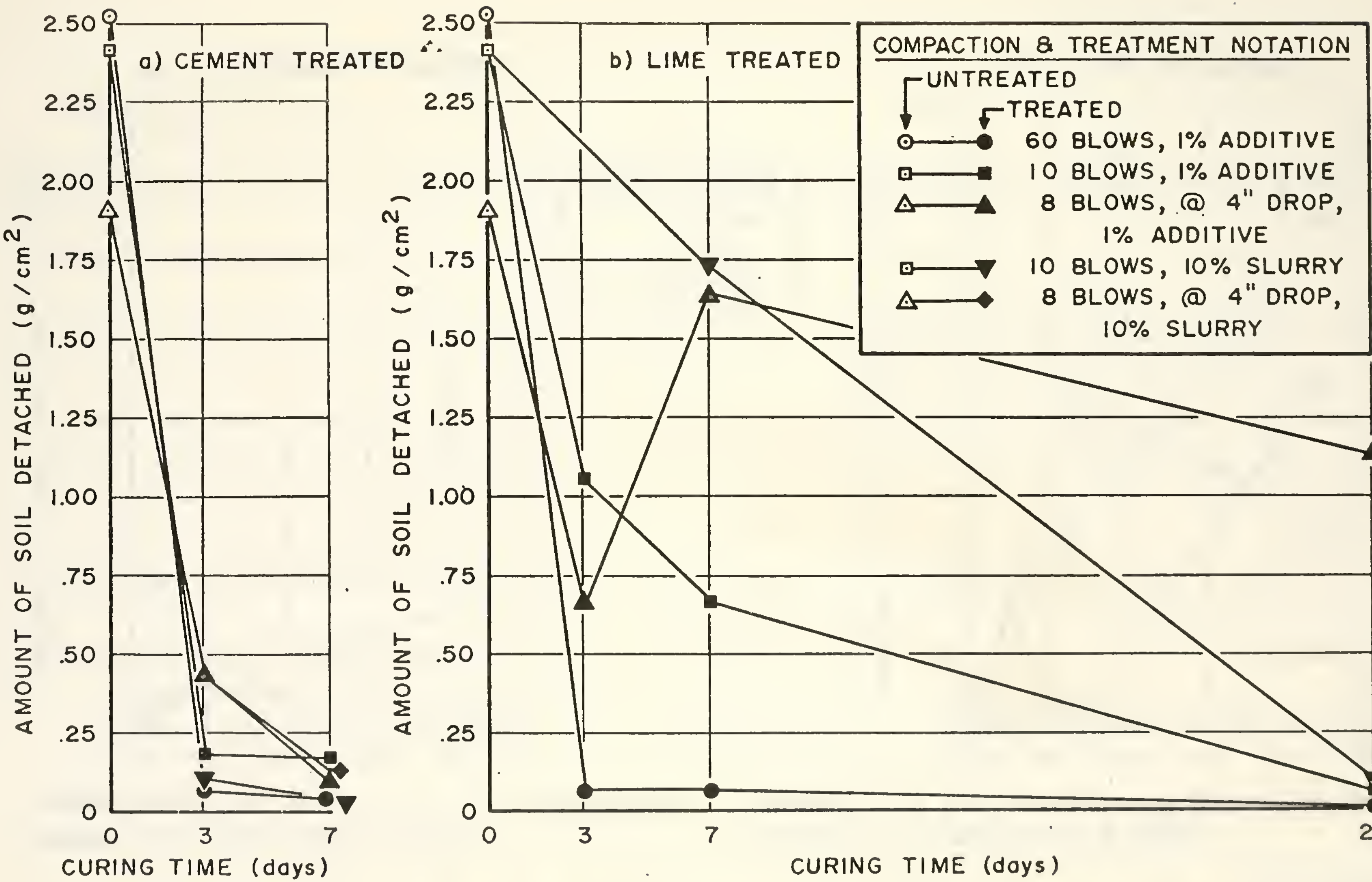


FIG. 23 AMOUNT OF SOIL DETACHED VS CURING TIME, WITH A VARIATION IN STABILIZING TREATMENT AND COMPACTIVE EFFORT: GLACIAL OUTWASH.

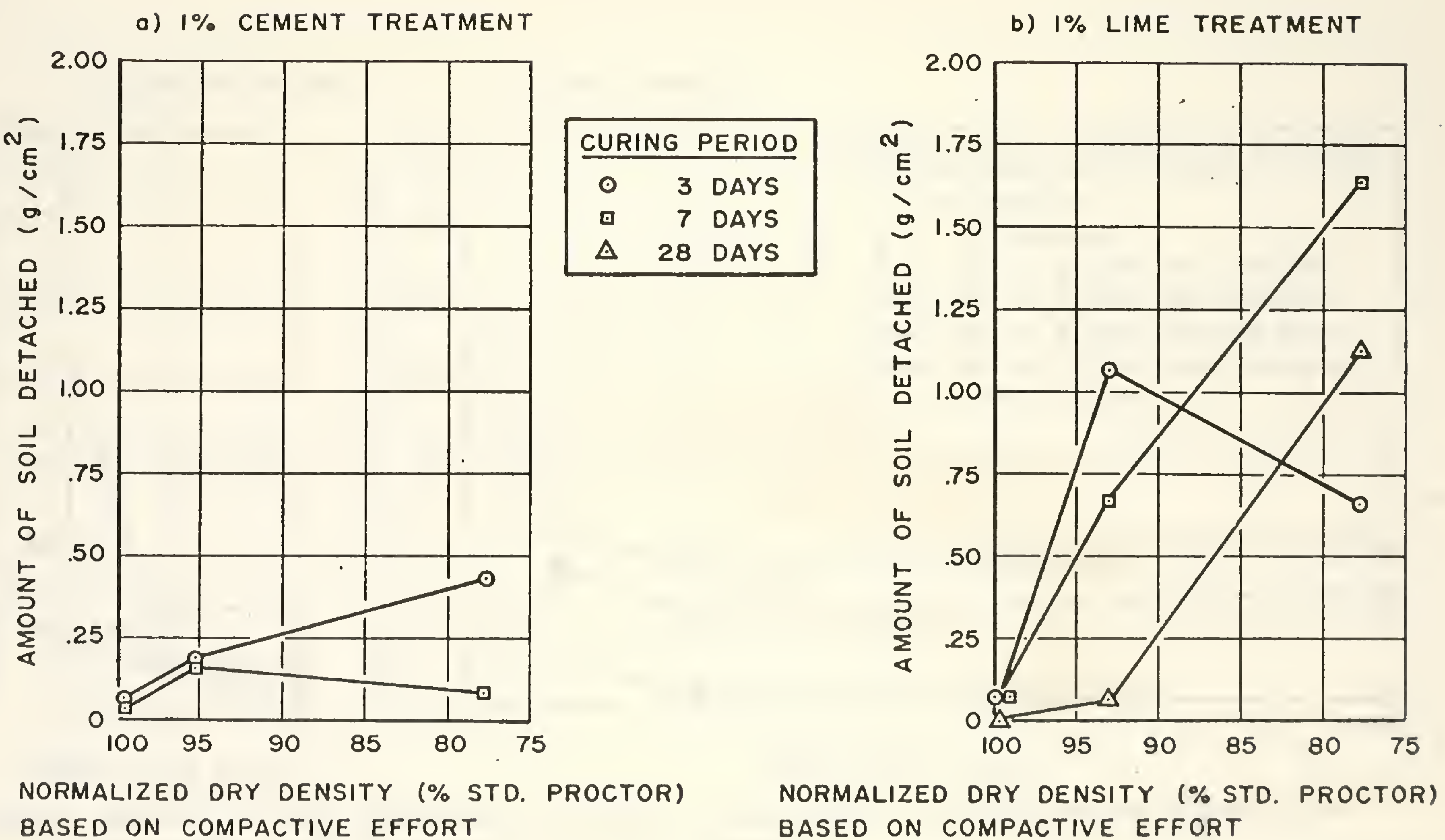


FIG. 24 EROSION LOSSES OF GLACIAL OUTWASH AS A FUNCTION OF STABILIZER, NORMALIZED DRY DENSITY AND CURING PERIOD.

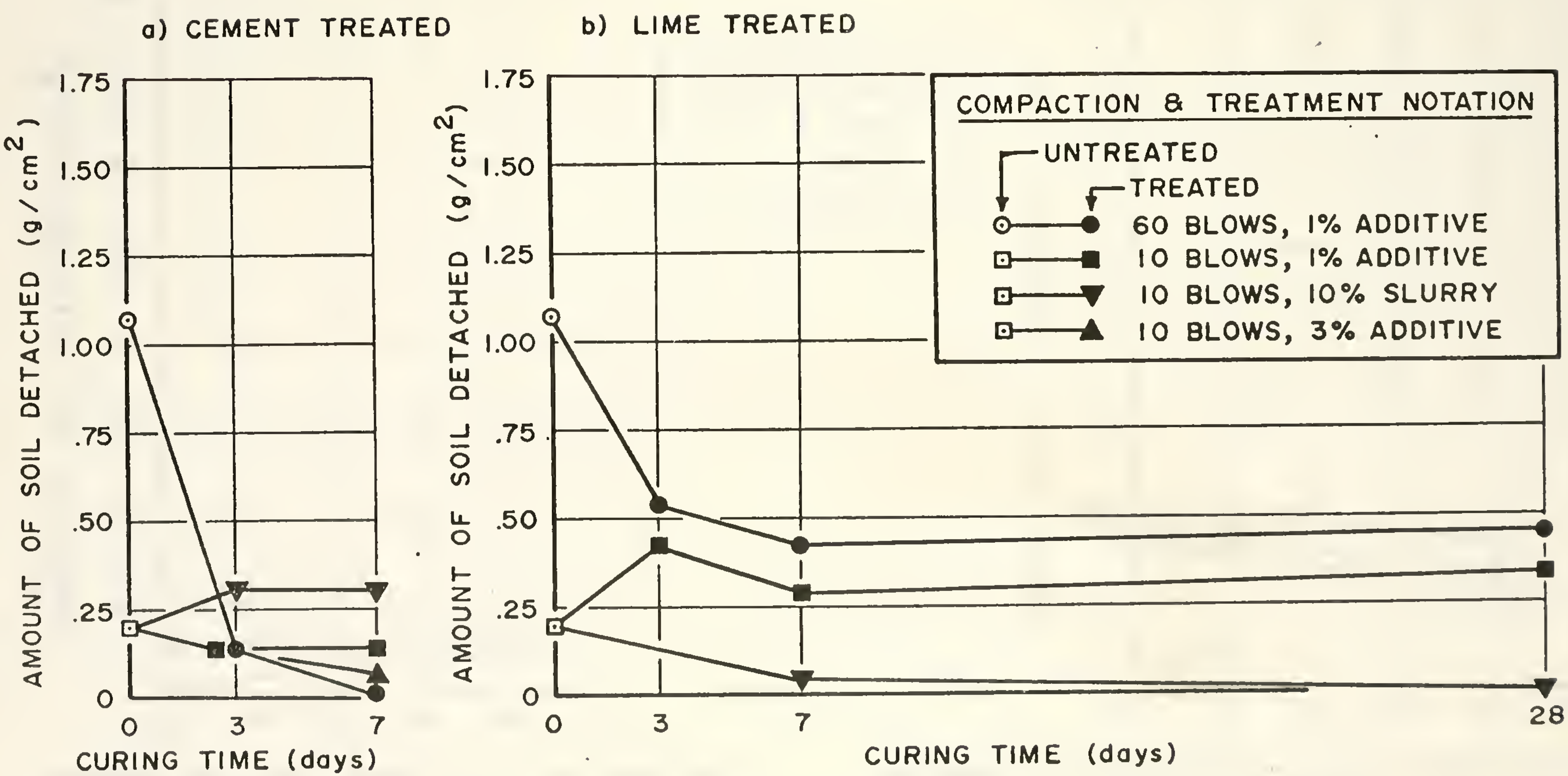


FIG. 25 AMOUNT OF SOIL DETACHED VS CURING TIME, WITH A VARIATION IN STABILIZING TREATMENT AND COMPACTIVE EFFORT: ROMNEY.

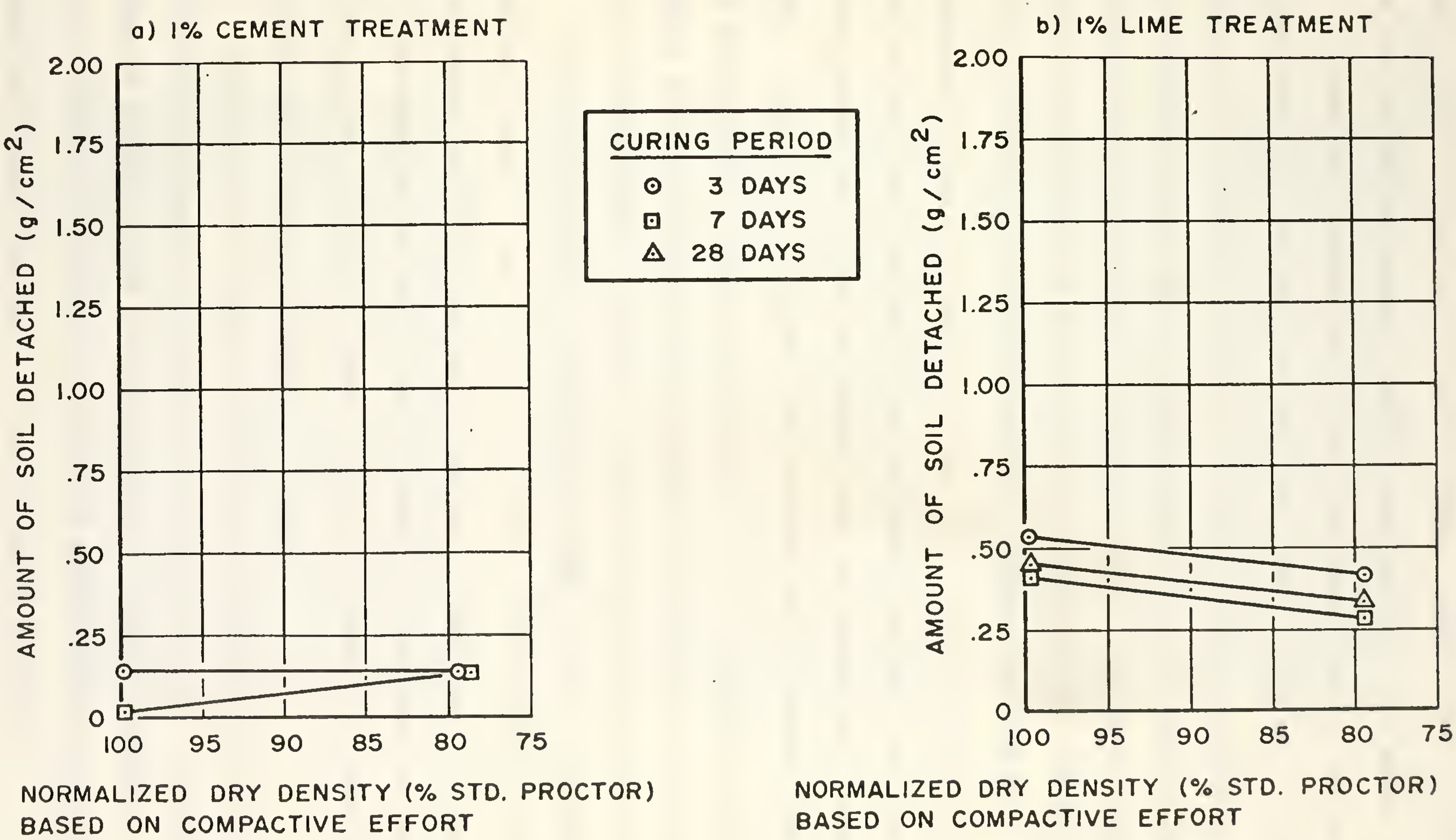


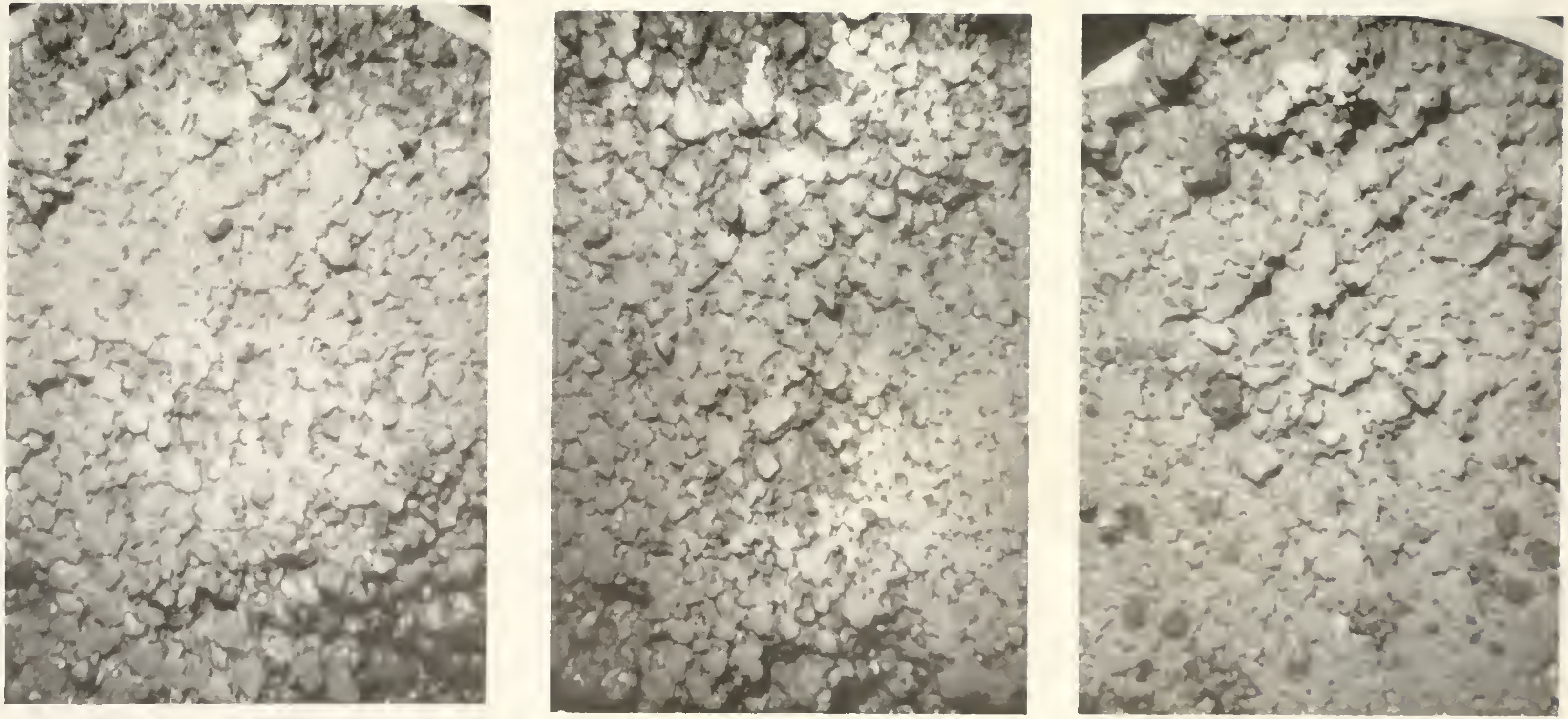
FIG. 26 EROSION LOSSES OF ROMNEY AS A FUNCTION OF STABILIZER, NORMALIZED DRY DENSITY AND CURING PERIOD.

less attractive than cement stabilization. Another limiting factor is the high pH environment, possibly unsuitable for the growth of grass.

Graphical presentations of soil loss versus curing time for lime-stabilized soils are shown in Figs. 19b, 21b, 23b and 25b. It can be seen that for Blue and Tan Clay Tills the erosion resistance is slow in developing, but after a curing period of 28 days, erosion losses are insignificant for Blue Clay Till (erosion loss is 95 times less than the untreated specimen) and for Tan Clay Till (erosion loss is 285 times less than the untreated specimen). Glacial Outwash soil appeared to react more quickly; after three curing days the erosion loss was 40 times less than that of the untreated specimen, and after a curing period of 28 days the erosion loss was reduced by a factor of 420. Lime-stabilized Romney soil, however, has an erosion loss at 28 days only 2-1/2 times less than that of the untreated specimen. Romney soil apparently requires a higher percentage of hydrated lime as it does of cement in order to create effective cementitious bonding.

Macrophotographs of lime-stabilized Blue Clay Till and Romney soil are shown in Figs. 17c and 17d, and 27, respectively, to exhibit the appearance of the specimens after the standard rainfall tests. As indicated earlier, Blue Clay Till shows an improvement as the curing period increases, whereas Romney soil shows no decrease in erosion loss beyond seven days of curing.

Generally, the results indicate that lime stabilization can be as effective as cement stabilization in the long run, but it lacks the speed of reaction which is characteristic of cement treatment. It also appears that stabilizer contents in excess of one percent are required to stabilize heavy clay soils against erosion.



(a) (b) (c)

Fig. 27 Romney Soil Treated with 1% Lime with a Variation in Curing Period
(a) 3 curing days (b) 7 curing days (c) 28 curing days
(all specimens at standard density)

The Effect of Reduced Compaction

As in the previous section, the soil was stabilized with hydrated lime or Portland cement at one percent of dry soil weight. This time it was desired to observe any change in erosion loss caused by reductions in compactive effort. As described before on page 26, the compaction level was controlled by the number of blows and the fall height of the 2.62 pound hammer (Fig. 4). 60, 30 and 10 blows with a drop height of 12 inches, and 8 blows with a drop height of 4 inches were used to produce densities of approximately 100, 96, 90, and 78 percent of Standard Proctor dry density, respectively. All treated specimens reacted favorably even at reduced density, but a general trend indicated that as the compactive effort was reduced the erosion loss increased. However, each of the four soils tested had its own individual response which will be subsequently discussed as relating to cement or lime treatment.

Portland Cement Treatment

As previously stated when discussing "standard density" treated specimens, cement treated soils react quickly to produce the cementitious bonding of clay particles and thus create the stabilized surface desired at a minimal expense of time. This rapid reaction also holds true under reduced compactive effort, even at densities as low as 78 percent of Standard Proctor density. Blue Clay Till (Figs. 19a and 20a) has shown excellent stabilization characteristics, with a reduction in compactive effort producing only a small increase in erosion loss. At the lowest compactive effort used (which simulates field density) the erosion losses at three and seven curing days were 8 and 12 times less,

respectively, than that for the untreated specimen at Standard Proctor density. At a density of approximately 90 percent of Standard Proctor density the erosion loss was 40 times less than that for the untreated specimen at the same density, and 70 times less than that for the untreated specimen at standard density. Similar results can be seen for Tan Clay Till (Figs. 21a and 22a).

Macrophotographs for cement-stabilized Blue Clay Till after rainstorm exposure (Fig. 28) show the differences in specimen surface appearance for densities of approximately 100, 90, and 78 percent of Standard Proctor density (keeping the curing period constant at seven days). The difference in appearance reflecting more erosion with decreasing density is also typical for Tan Clay Till and Glacial Outwash soil. The Glacial Outwash soil (Figs. 23a and 24a) has one abnormality, however, of having less erosion loss at the compactive level representing field density as opposed to the treated specimen at 95 percent of standard density, keeping the curing period constant at seven days.

Romney soil (Figs. 25a and 26a) behaves differently than the other soils tested. At Standard Proctor density, the loss after seven days cure is on the order of eight times less than that of the comparable untreated Romney soil. However, untreated Romney soil lightly compacted at 10 blows compactive effort (which yields 78 percent of Standard Proctor density) shows much better erosion resistance than the fully compacted untreated soil. The additional erosion resistance experienced by adding one percent cement is insignificant.

(a) (b) (c)

Fig. 28 Blue Clay Till Treated with 1% Cement at 7 Curing Days with a Variation in Compactive Effort (a) 60 blows (b) 10 blows (c) 8 blows at 4 inch drop

It was thought that there was an insufficient amount of stabilizer incorporated with the soil and a test was performed using a cement content of three percent of dry soil weight and a specimen density of 78 percent of standard. This resulted in an erosion loss half of that for the corresponding one percent treatment specimen, indicating that for heavier clays like Romney increased stabilizer contents can be used as required to produce a more erosion resistant surface.

Recapitulating, the general trend of erosion loss with reduced compaction (keeping the cement treatment and curing period constant) is that the erosion resistance is lowered by reducing the level of compaction, but not by much. Therefore, it might be economically advantageous to stabilize at the lower compactive effort where the slight additional erosion loss can be tolerated.

Hydrated Lime Treatment

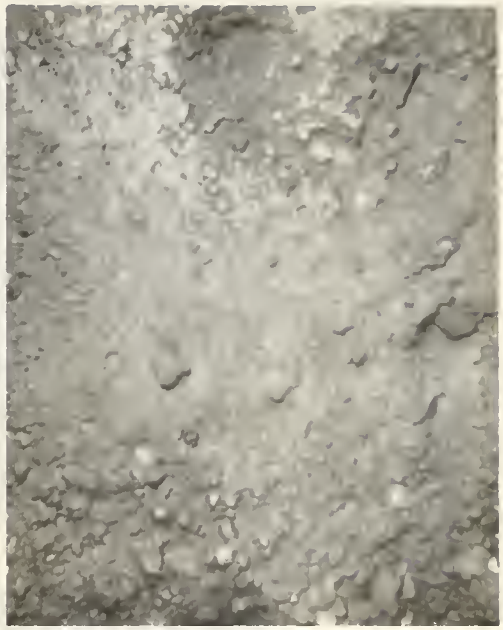
It was stated previously that lime reacted slowly with the soil particles, and this phenomenon is more evident for specimens at reduced compactions. Blue and Tan Clay Tills (Figs. 19b, 20b, 21b, and 22b) are relatively similar in that the erosion loss increases with decreases in compaction level, and the effect is maintained as the curing period increases. For Blue Clay Till stabilized with one percent lime and cured for three days, the erosion losses for standard density and simulated field density were seven and two times less, respectively, than the untreated standard density specimen. Very low density specimens are not well stabilized. If the erosion loss for the simulated field density lime treated sample is compared to the untreated sample of the same density, a reduction of only 25 percent at

three curing days is observed. After 28 days, however, the erosion loss is reduced by 80 percent, a somewhat better result.

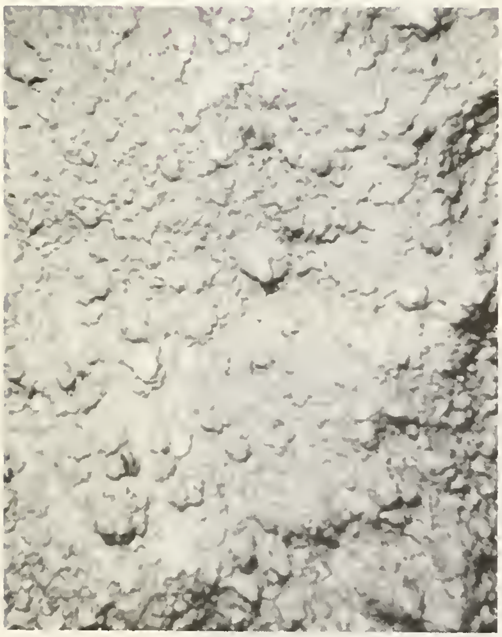
Blue Clay Till macrophotographs (Fig. 29) show by the appearance of the specimen surfaces the reduction in resistance to erosion after a constant curing time of seven days that accompanies reduced compactive efforts. Fig. 30 shows the influence of the curing period on the stabilized soil, the surface being less eroded at longer curing periods (keeping the compactive effort constant). Macrophotographs (Fig. 31) of Tan Clay Till show clearly the effects of both factors: the more compacted specimen eroding much less than the lightly compacted specimen at a given age, but both types improving with age.

The Glacial Outwash soil (Figs. 23b and 24b), however, stabilizes rapidly at standard density with lime; the additional decrease in erosion loss from 3 to 28 curing days is insignificant because even the early erosion loss is only 1/40 of that for the untreated standard density specimen. However, Glacial Outwash soil does not behave this well at reduced compaction. For the specimens compacted at 10 blows and treated with lime, the initial (three day) erosion loss is as much as half of that for untreated specimens at the same density; but by 28 days the erosion loss has become insignificant (reduction by a factor of 40). The specimen with the lightest compactive effort (eight blows at a four inch drop) when treated with one percent lime showed a small apparent improvement in three curing days, but this improvement was apparently lost in the seven day curing period. It is likely that the three day cured specimen may have been improperly prepared and tested and thus the result represents an experimental

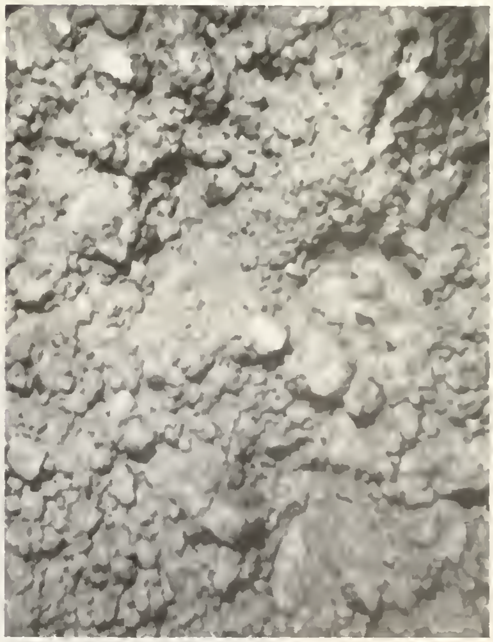
(a)



(b)

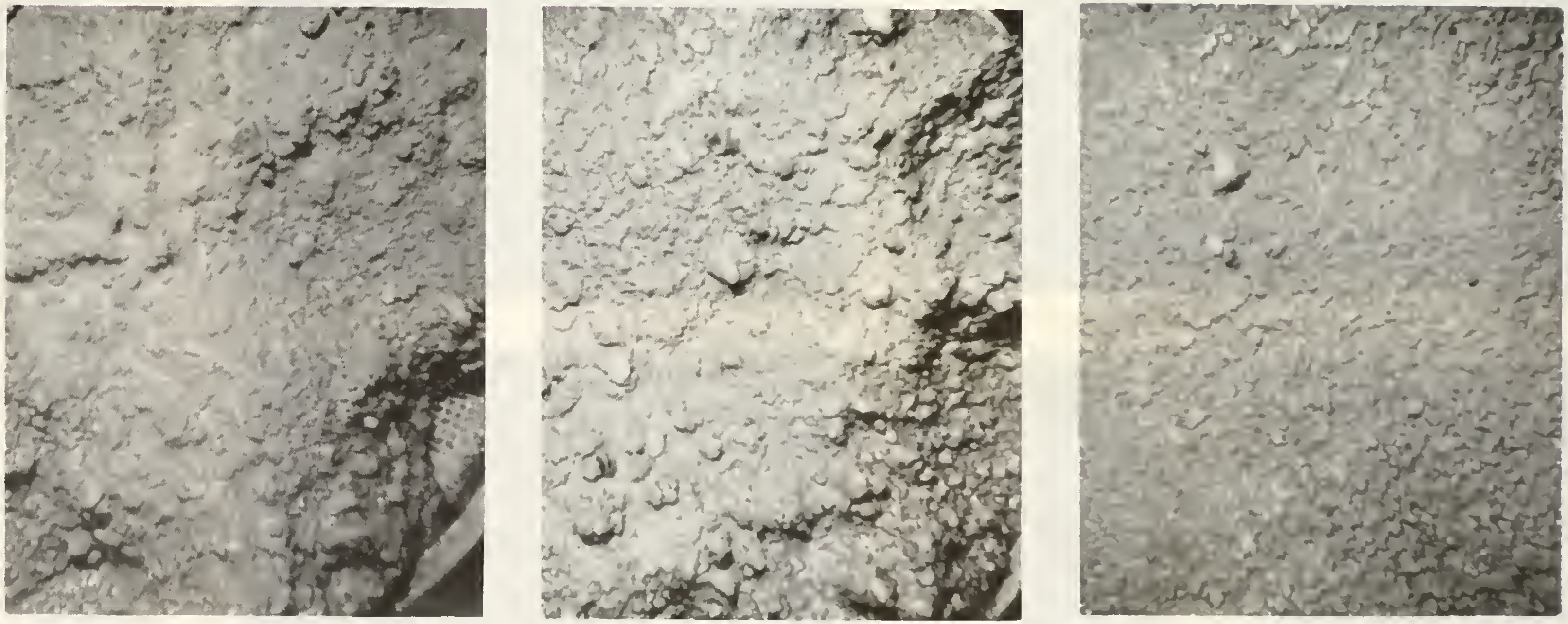


(c)



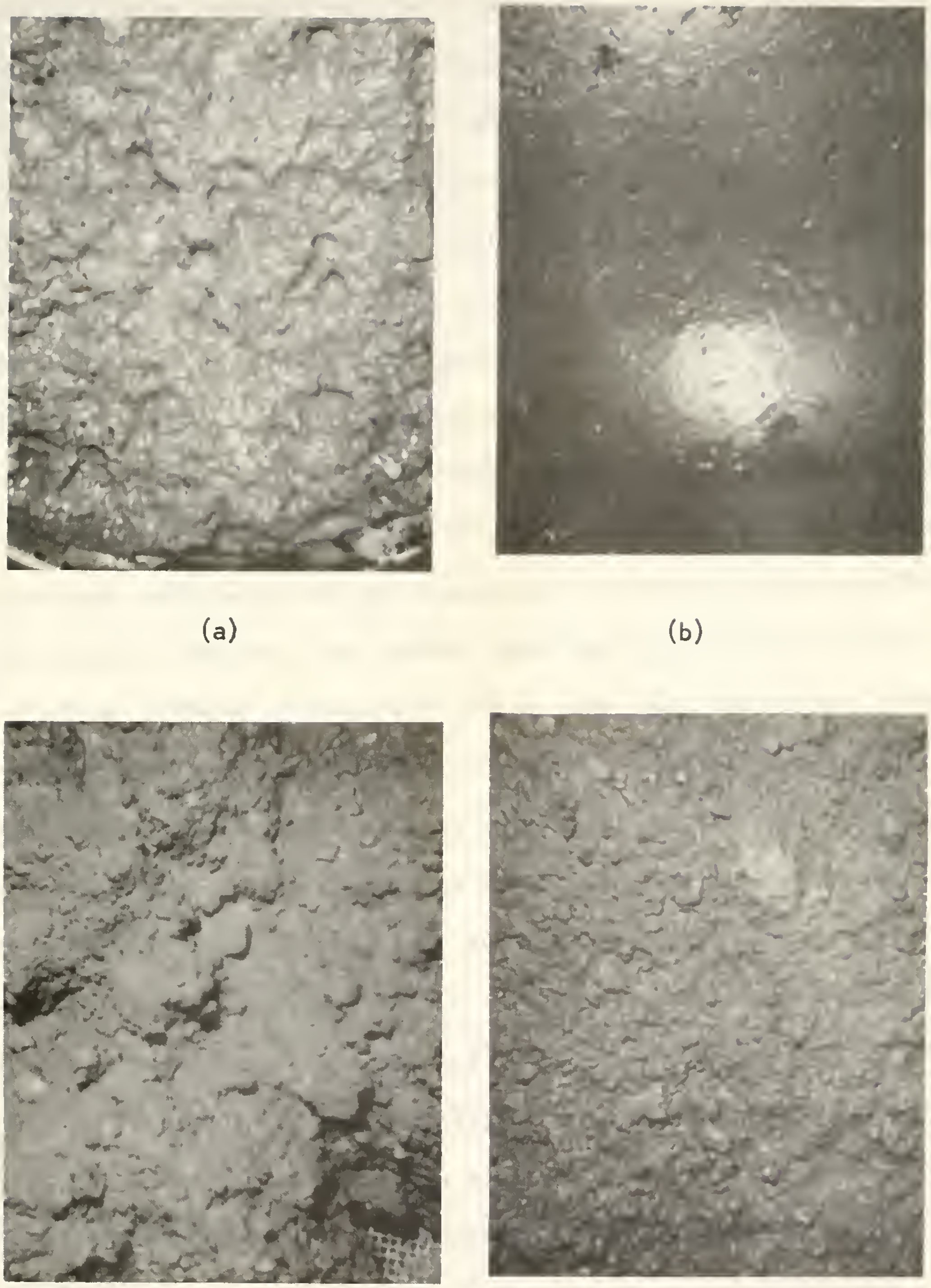
(d)

Fig. 29 Blue Clay Till Treated with 1% Lime at 7 Curing Days with a Variation in Compactive Effort
(a) 60 blows (b) 30 blows (c) 10 blows
(d) 8 blows at 4 inch drop



(a) (b) (c)

Fig. 30 Blue Clay Till Treated with 1% Lime at a Compactive Effort of 10 Blows with a Variation in Curing Period
(a) 3 curing days (b) 7 curing days (c) 28 curing days



(a) (b)

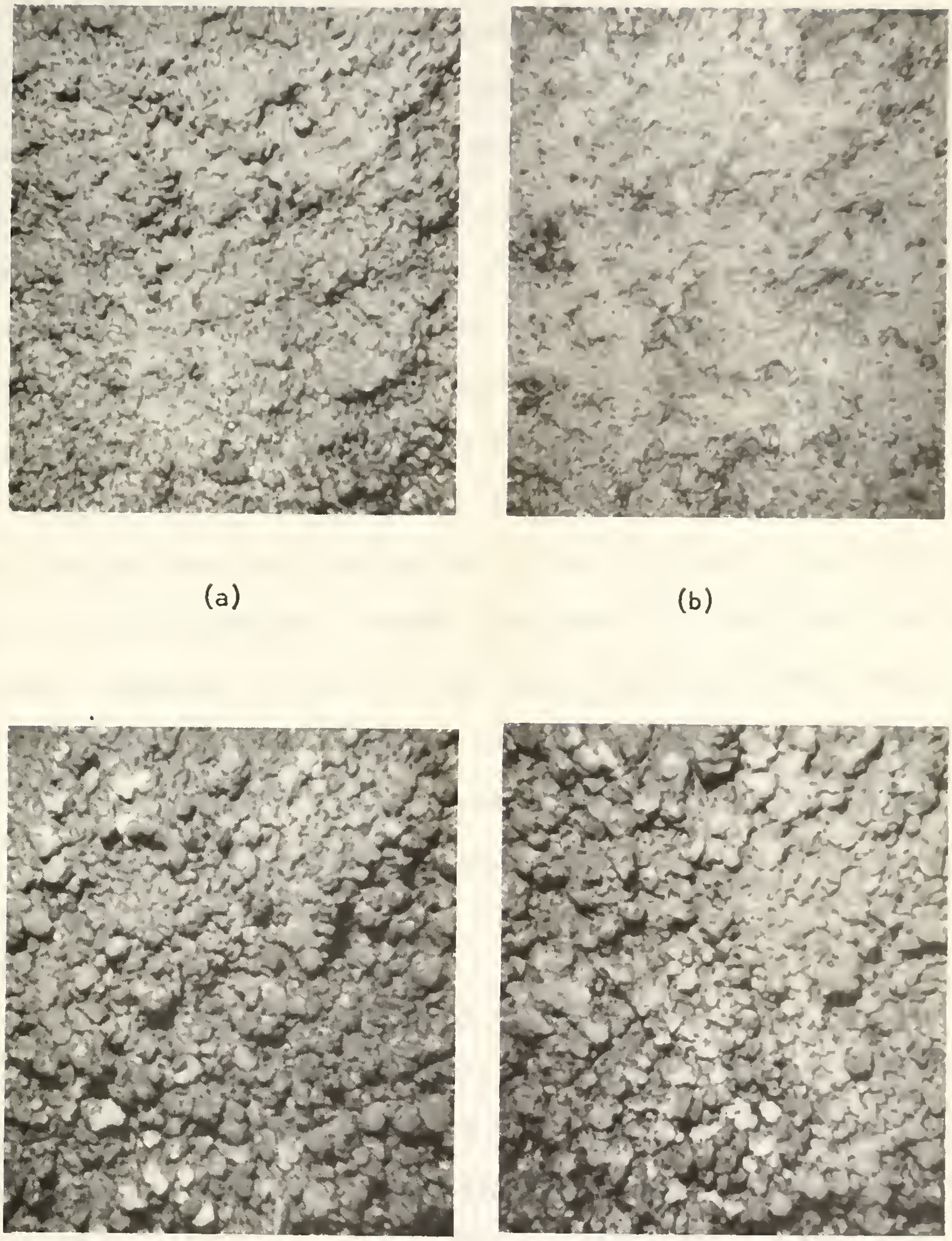
(c) (d)

Fig. 31 Tan Clay Till Treated with 1% Lime with Variations in Compactive Effort and Curing Period (a) 60 blows at 3 curing days (b) 60 blows at 28 curing days (c) 10 blows at 3 curing days (d) 10 blows at 28 curing days

error, but it is included here because of the inability to positively explain the phenomenon. After 28 days of curing, the erosion loss was reduced only 40 percent compared to untreated soil suggesting that a more reasonable compactive effort is required to attain resistance to erosion, at least at a treatment level as low as one percent of lime. It should also be stated here that Glacial Outwash at reduced compaction was very difficult to handle because of its loose, granular structure. Tan Clay Till is similar to Glacial Outwash soil in that the erosion loss at reduced compaction and short curing period is large.

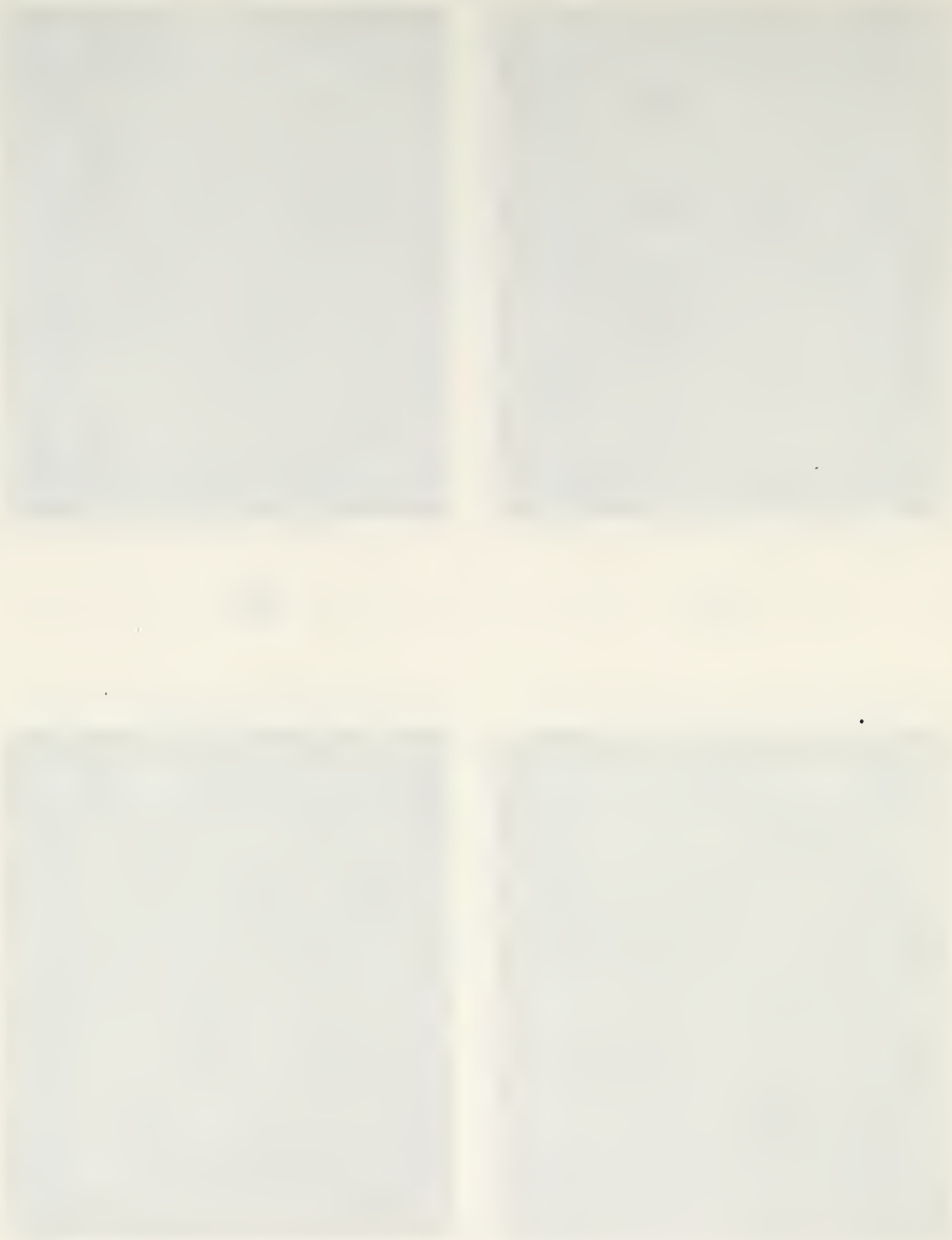
Macrophotographs for Glacial Outwash soil (Figs. 32a and b) show the specimen surface to be more eroded at the lower compactive effort. At the standard density, the treated specimen still retains much of the original surface; this is not true at the lower compactive level.

The results for lime treated Romney soil (Figs. 25b and 26b) differ in that they show an erosion loss versus curing time trend similar to the other soils, but the total reduction is small. The minimum erosion loss for specimens treated at standard density is only 2-1/2 times less than that for the untreated specimen at standard density, regardless of curing period. At a compactive effort of 10 blows, the treated specimens actually erode more than the comparable untreated specimens. Thus for low compactive effort, it can be seen that the introduction of only one percent stabilizer will be detrimental to the soil's resistance to erosion, even though less erosion loss is observed at this density as opposed to specimens prepared at Standard Proctor density. On the other hand, at a three percent stabilizer level, virtually complete erosion resistance results even at a low compactive effort.



(a) (b) (c) (d)

Fig. 32 1% Lime Treated Glacial Outwash and Romney Soils at 7 Curing Days with a Variation in Compactive Effort (a) Glacial Outwash soil at 60 blows (b) Glacial Outwash soil at 10 blows (c) Romney soil at 60 blows (d) Romney soil at 10 blows



It can be seen from the macrophotographs of lime treated Romney soil (Figs. 32c and d) that the specimen surfaces appear similar in erosion and structure for 60 and 10 blow compactive efforts, keeping the curing period constant at seven days. The aggregated soil lumps were previously shown in Fig. 16 for the untreated specimens where these aggregations were more evident for the less compacted specimen. The problem then with Romney soil may involve penetration of the stabilizer into the aggregate masses which, if not sufficiently achieved, may result in insufficient stabilization to be effective.

Summarizing, the effect of reducing compactive effort on stabilized specimens was observed as a slight decrease in the effectiveness of the stabilization. However, the heavy clay exhibited a further decrease in erosion loss upon reduced compactive effort when treated with lime. For the glacial soils treated with lime, it was observed that the time delay required to procure effective stabilization was more pronounced than that for the specimens compacted at Standard Proctor density.

Slurry Application on Untreated Soil

It was previously mentioned that the slurry concentration of 10 percent of either lime or cement was indicated to be appropriate from a series of qualitative laboratory experiments on Blue Clay Till which showed this concentration to penetrate the soil appreciably in the least amount of time. A total weight of 60 grams of slurry per four inch diameter specimen was found to be sufficient. It was also determined that compactive efforts less than that of Standard Proctor were necessary to facilitate slurry penetration. A series of rainfall tests,

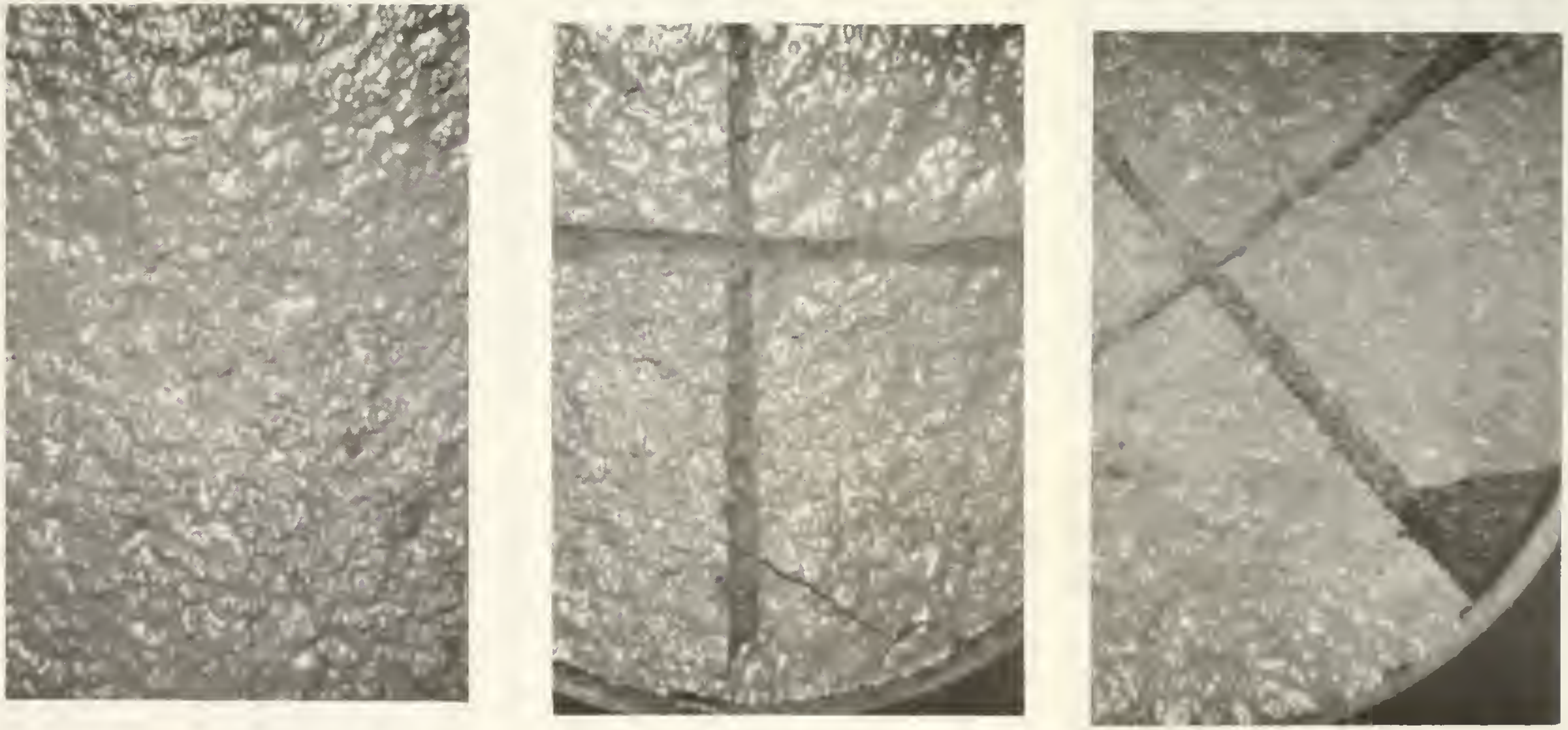
as previously described, were performed on untreated Blue Clay Till, Glacial Outwash soil, and Romney soil at a compactive effort that yielded approximately 90 percent of Standard Proctor density. Later it was decided to investigate the effect of slurry treatment on specimens prepared at simulated field densities. Blue Clay Till and Glacial Outwash soil were tested to show the differences in effect attained for two very different soil types.

The results indicate that cement or lime slurry stabilization can be quite effective, sometimes showing better erosion resistance than attained by mixing the stabilizer and soil and then compacting to less than Standard Proctor density.

Portland Cement-Slurry Treatment

The cement slurry on Glacial Outwash soil (Fig. 23a) prepared at a compactive effort of 10 blows produced good stabilization with an erosion loss in seven days 60 times less than that for the untreated specimen at the same density. It was more erosion resistant than the reduced compaction specimens with one percent cement mixed with the same soil prior to compaction. Fig. 33 displays macrophotographs for the Glacial Outwash specimen as follows: before rainfall testing; ready for rainfall testing with the surface purposely scarred to encourage erosion loss due to the cracking of the slurry crust; and after rainfall testing showing very minimal signs of erosion. The small wedge that is missing in Fig. 33c was caused by the accidental crack (shown in Fig. 33b) due to handling before rainfall testing.

Glacial Outwash soil was also tested at simulated field density; the 10 percent cement slurry provided good erosion resistance, the loss



(a) (b) (c)

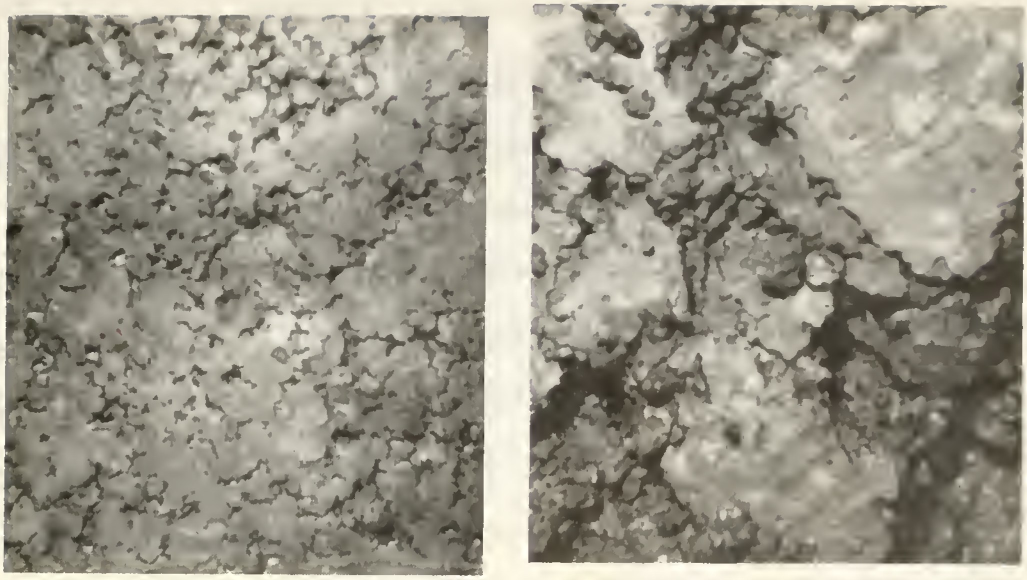
Fig. 33 Glacial Outwash Soil at 10 Blows Compactive Effort with 10% Cement Slurry Concentration at 3 Curing Days (a) before rainfall test (b) before rainfall test with surface purposely scarred (c) after rainfall test

being 15 times less than that for the untreated specimen at the same simulated field density.

However, slurry treated Romney specimens previously prepared at a compactive effort of 10 blows gave unsatisfactory results (Fig. 25a) and showed an increase in erosion loss over the untreated specimen at the same density. This erosion increase was probably due to the difficulty the cement slurry had in penetrating the specimen and in the reaction process had actually loosened the clay particles close to the specimen's surface. From Fig. 34a it can be seen that wherever the cement penetration was weak it was susceptible to both rainfall and local runoff erosion (from the stabilized portions of the specimen's surface).

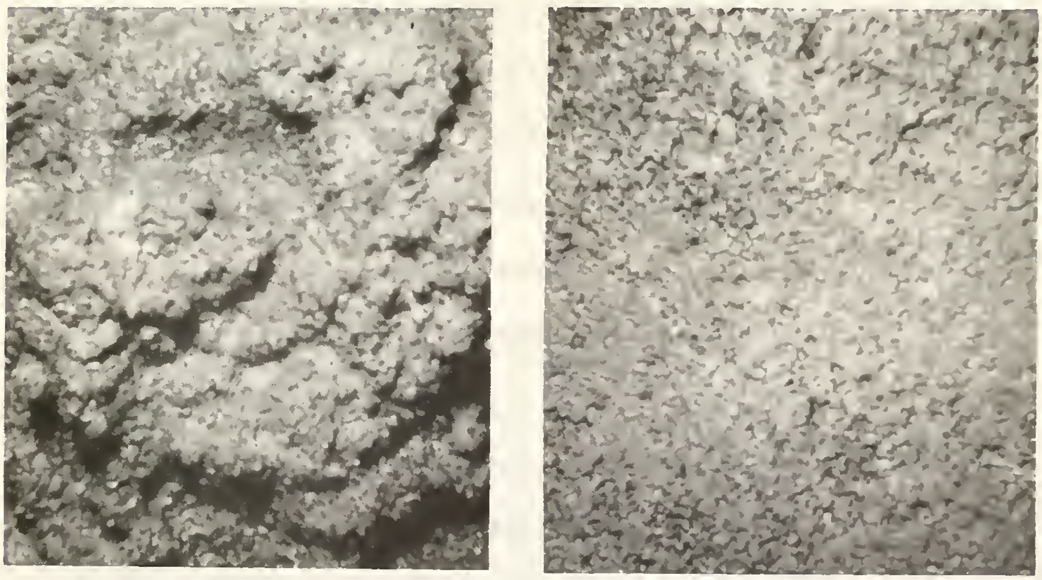
Blue Clay Till (Fig. 19a) prepared at the reduced compactive effort of 10 blows, reacted well with the 10 percent cement slurry. Although the reduction in soil loss was small after three curing days, the erosion loss reduced sufficiently after seven days to compare favorably with the results attained by more conventional additive-soil mix plus compaction methods. Blue Clay Till at simulated field density was tested after a curing period of seven days; the resulting erosion loss reduction was similar to that of the 10 blow compacted specimens with the same stabilizing treatment and curing period.

Generally, it is observed that cement slurry treated specimens show reduced soil erosion losses similar to those for the additive-soil mix methods previously described; Romney soil, the heavy montmorillonitic clay, showed an increase in erosion loss rather than a decrease and is obviously not a suitable soil for this kind of treatment.



(a) (b)

Fig. 34 Slurry Treated Romney Soil at 10 Blows Compactive Effort and 7 Curing Days with a Variation in Stabilizer (a) 10% cement slurry concentration (b) 10% lime slurry concentration



(a) (b)

Fig. 35 Glacial Outwash Soil at 10 Blows Compactive Effort, Treated with 10% Lime Slurry Concentration with a Variation in Curing Period (a) 7 curing days (b) 28 curing days

Hydrated Lime-Slurry Treatment

Glacial Outwash soil (Fig. 23b), treated with a ten percent lime slurry after preparation at a compactive effort of 10 blows, was slow in reacting to create a useful stabilized surface. The erosion loss at seven days was only 30 percent less than that for the untreated specimen. However, after 28 curing days satisfactory results were obtained, with the erosion loss being 25 times less than that for the untreated specimen. These results show that if the lime slurry-soil can cure for approximately a month, adequate resistance will be realized. Macrophotographs (Fig. 35) show a vast improvement between 7 and 28 days of curing for specimens compacted at 10 blows. Small crusts of lime are noticeable on the seven day cured specimen, which was greatly eroded.

Romney soil (Fig. 25b), after preparation at only 10 blows, was treated with the 10 percent lime-slurry and cured for 7 and 28 days. The treatments were successful, the resulting erosion losses after rainfall testing being 5 to 25 times less than that for the untreated specimen. Macrophotographs for Romney soil (Fig. 34b) show the well-knit aggregated structure which had reacted well with the heavy dose of lime-slurry.

Blue Clay Till (Fig. 19b) responded very well to lime slurry treatment after preparation at both reduced compactive levels. The erosion losses were on the order of 35 times less than that for the untreated specimens. Blue Clay Till has been a favorable soil for all the other stabilization methods so it is no surprise that the slurry treatment would result in excellent erosion protection. Macrophotographs (Fig. 36) exhibit the appearance of the specimen's surface

(a) (b) (c)

Fig. 36 Blue Clay Till at 10 Blows Compactive Effort, Treated with 10% Lime Slurry Concentration at 7 Curing Days (a) before rainfall test (b) before rainfall test with excess slurry removed from the specimen's surface (c) after rainfall test

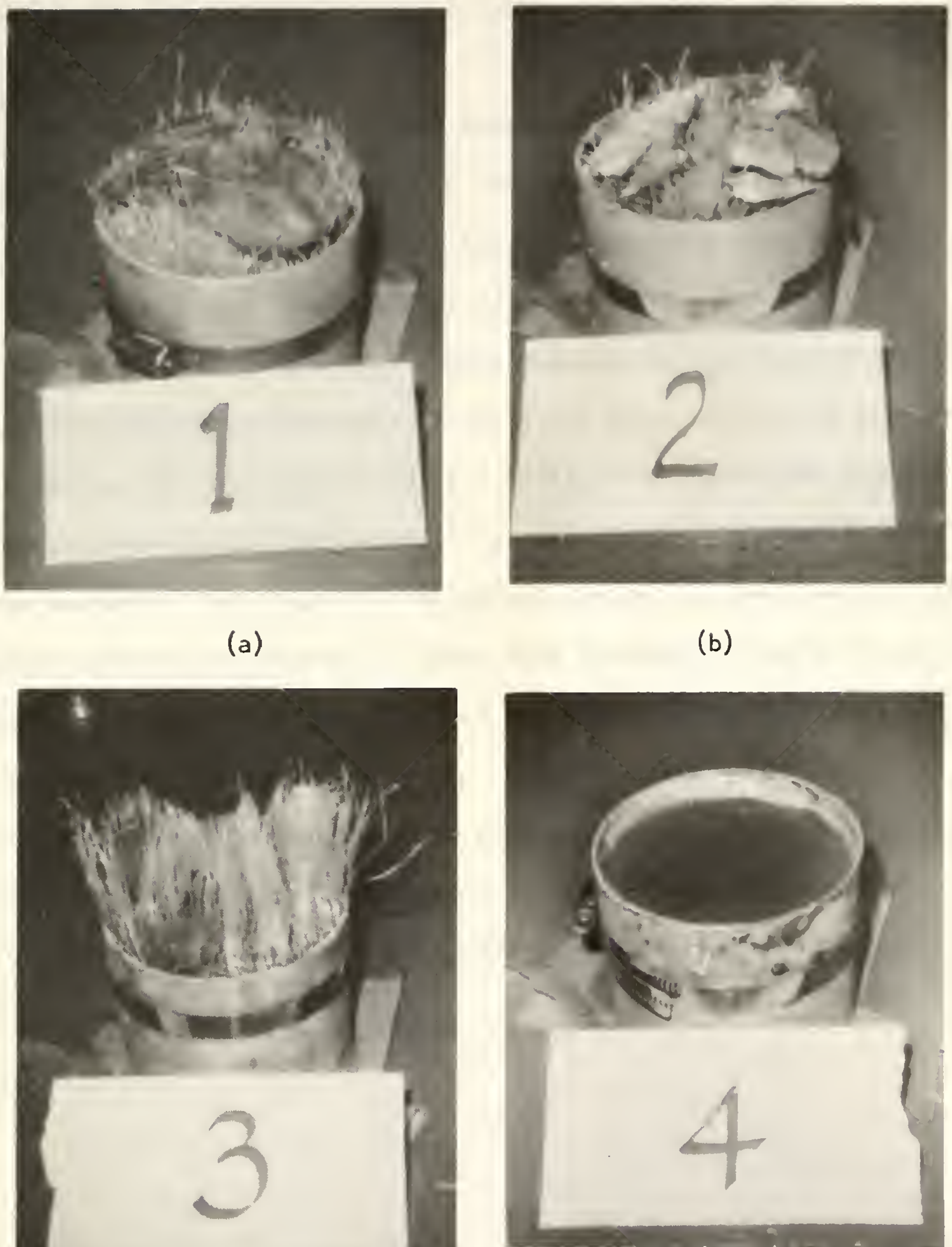
(a) before rainfall testing, showing part of the soft lime-slurry removed; (b) before rainfall testing but after all of the remaining slurry (that had not penetrated the soil) had been removed; and (c) after rainfall testing, showing no noticeable erosion.

Summarizing, lime-slurry treated samples have been favorable in reducing erosion loss to insignificant levels after some weeks. Of course, the problem remains with the slow development of the stabilized product, but this is also true for the other lime-soil stabilizing methods.

The Ability of Stabilized Soils to Grow Grass

A qualitative laboratory study was undertaken to examine the effects of the stabilizer on the potential growth of grass. Four Blue Clay Till specimens (Fig. 37) were prepared at simulated field density to be treated in the following four methods, using Alta fescue grass:

1. The untreated soil was compacted to simulated field density in a 4-1/2 inch deep mold and covered with a partial layer of Alta fescue seed, which was in turn covered with 1/4 inch layer of lightly compacted soil. A 10 percent cement-slurry was then poured over the soil.
2. The same method of preparation, except that a 10 percent lime-slurry was used.
3. The soil was mixed with one percent cement, compacted in the mold, a layer of seed spread, and a 1/4 inch thick covering of slightly compacted stabilizer-treated soil applied.



(a) (b)

(c) (d)

Fig. 37 Blue Clay Till at Simulated Field Density with a Variation in Stabilization Method to Show the Corresponding Ability to Grow Grass (a) 10% cement slurry concentration (b) 10% lime slurry concentration (c) 1% cement-soil mix (d) 1% lime-soil mix

4. The same method, substituting one percent lime for the cement.

The specimens were cured for seven days at nearly 100 percent relative humidity, then exposed to sunlight and artificial light for a period of three days being kept appropriately watered.

The results are shown in Fig. 37 which demonstrates that all treatments except for method 4 showed a potential for growing grass. The macrophotographs show that as the grass grew, it exerted pressure against the 1/4 inch stabilized soil crust until it cracked and was lifted, exposing the thick stand of grass. Sample 4 failed to grow grass because of the high pH environment created by the lime-soil mix, whereas sample 2 was successful with lime because the depth of penetration was probably less than 1/4 inch and thus did not influence the pH surrounding the seed.

The specimens were allowed to continue to grow for a period of several months after the photographs in Fig. 37 were taken and developed a thick, uniform, and apparently healthy stand of grass.

ECONOMIC ASPECTS

An economic analysis of the costs of providing erosion protection by the lime or cement-based stabilization treatments considered in this report is difficult to perform because of the large number of assumptions that have to be made.

It is possible to form an idea of comparative costs by comparing such methods with the expenditures associated with present methods of providing erosion protection.

In current practice, such protection is considered to be permanent in nature and is confined largely to slopes adjacent to roadways. When examining relative costs, one should make allowances for the difference in concepts and the differences in function between the treatments contemplated here and the conventional practices.

The following methods of providing permanent protection for slopes have been considered and per-acre-costs are calculated in Table 3 and shown comparatively in Figure 38.

1. Regular dumped riprap
2. Revetment riprap
3. 12 inch hand-laid riprap
4. Sodding
5. Conventional grass seeding: agricultural lime, fertilizer, seed, and mulch
6. Agricultural lime, fertilizer, seed, and jute netting

In the analysis, lime or cement stabilization has been considered for a design depth of stabilized layer of two inches, with a level of two percent additive such as might be recommended for field application. Costs for the soil-additive mixing plus compaction treatment are calculated, with separate calculations being made for the alternate method of applying the additive in slurry form on soil surfaces.

In addition, costs of combining seeding with these treatments have been calculated. All of the results appear in Table 4 and graphically in Figure 39.

The cost data (1974 base) presented in Tables 3 and 4 were compiled from information supplied by Cooper et. al. (Ref. 5) of the Roadside Development Division, Indiana State Highway Commission, and from information given informally be several contractors in Indiana, including Russell F. Davis, Inc., and McMahan-O'Connor Construction Company.

From Fig. 38, it is seen that riprap is an expensive form of stabilization and would be used only in critical cases where extensive water flows on steep slopes are expected. For the normal construction situation with moderate slopes, methods using riprap would be prohibitive. Falling in this same cost range are paved side ditches and other structures to divert or halt the flow of sediment. The cost for these structures ranges from \$6 to \$15 per linear foot, plus the cost of maintenance required to remove the collected debris.

As indicated in Fig. 38, the cost range of sodding is much less than of riprap applications, and hydroseeding of side slopes is somewhat less expensive yet.

Table 3 Costs of Conventional Methods of Slope Protection

Method	Cost per Unit ($)	Unit	Conversion Factor	Cost per Acre ($)
12" Handlaid Riprap	11.06	sq. yd.		53,530
Regular Dumped Riprap	9.51	sq. yd.		46,028
12" Deep Revetment Riprap	9.10	ton	$\frac{2\ \text{tons}}{\text{cu. yd.}}$	29,363
6" Deep Revetment Riprap	9.10	ton	$\frac{2\ \text{tons}}{\text{cu. yd.}}$	14,681
Sodding	1.62	sq. yd.		7,841
Seeding & Jute Netting:				
soil preparation	.113	sq. yd.		
seeding, fertilizer & jute netting (Ref. 22)	.45	sq. yd.		
TOTAL	.56	sq. yd.		2,725
Hydroseeding & Mulch:				
soil preparation	.113	sq. yd.		
agricultural limestone	15.30	ton	$\frac{1}{2}\ \frac{\text{ton}}{\text{acre}}$	
fertilizer	220.50	ton	800 lbs/acre	
seed	2.17	lb.	110 lbs/acre	
straw mulch	146.37	ton	2 tons/acre	
TOTAL	.244	sq. yd.		1,181

Unless otherwise specified, all estimates taken from Cooper et. al. (Ref. 5)

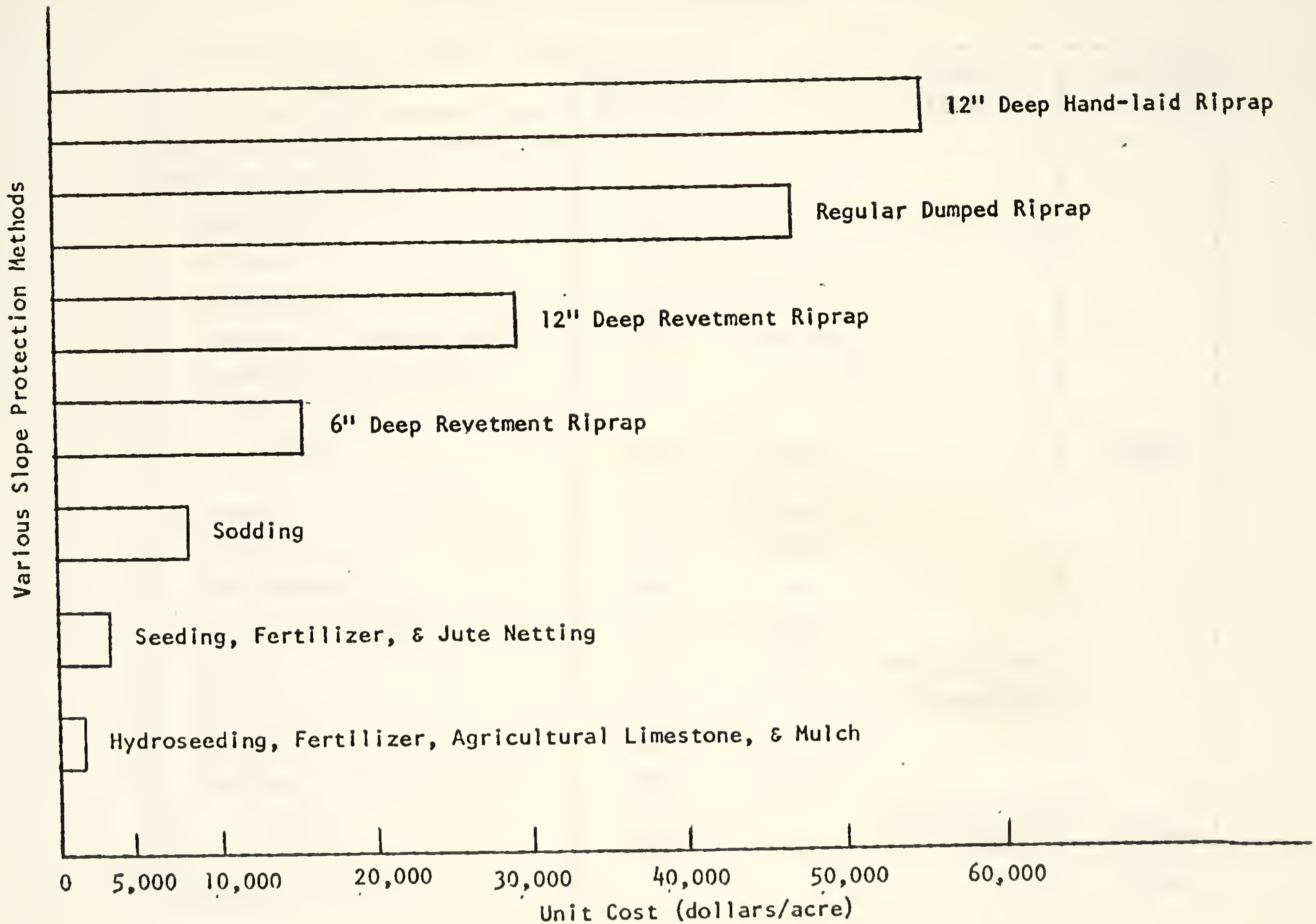


Fig. 38 Costs of Conventional Methods of Slope Protection

Table 4 Costs of Stabilization Methods

Method	Cost per Unit ($)	Unit	Conversion Factor	Cost per Acre ($)
Additive-Soil Mix & Compaction:				
a) soil preparation	.113	sq. yd.		
additive	.031*	lb.	3 lbs/sq. yd.	
mixing	.173	sq. yd.		
compaction	.047	sq. yd.		
overhead & external equip.	.214	sq. yd.		
profit & depreciation allowance	.16	sq. yd.		
TOTAL	.80	sq. yd.		3,872
b) grader	104	day		
water truck	160	day		
pulvi-mixer	244	day		
flat wheel roller	40	day		
fuel	.50	gals.	240 gal/day	
additive	.031*	lb.	3 lbs/sq. yd.	
labor	534	day		
overhead, profit, & risk	428	day		
TOTAL	1,853	day	2400 $\frac{\text{sq. yd.}}{\text{day}}$	3,736
Average of a) & b)				3,804

Table 4, cont.

Method	Cost per Unit ($)	Unit	Conversion Factor	Cost per Acre ($)
Additive-Slurry on Soil Surface:				
soil preparation	.113	sq. yd.		
additive	.031*	lb.	3 lbs/sq. yd.	
hydroseeder equipment & labor	.041	sq. yd.		
TOTAL	.25	sq. yd.		1,195
Additive-Soil Mix, Seeding, & Compaction				
fertilizer & seed	.069	sq. yd.		
additive-soil mix & compaction	3804	acre		
TOTAL	.855	sq. yd.		4,138
Seeding & Additive-Slurry on Soil Surface:				
fertilizer & seed	.069	sq. yd.		
additive-slurry on soil surface	.25	sq. yd.		
TOTAL	.319	sq. yd.		1,544

*Bulk from St. Louis, Missouri, to Rochester, Indiana

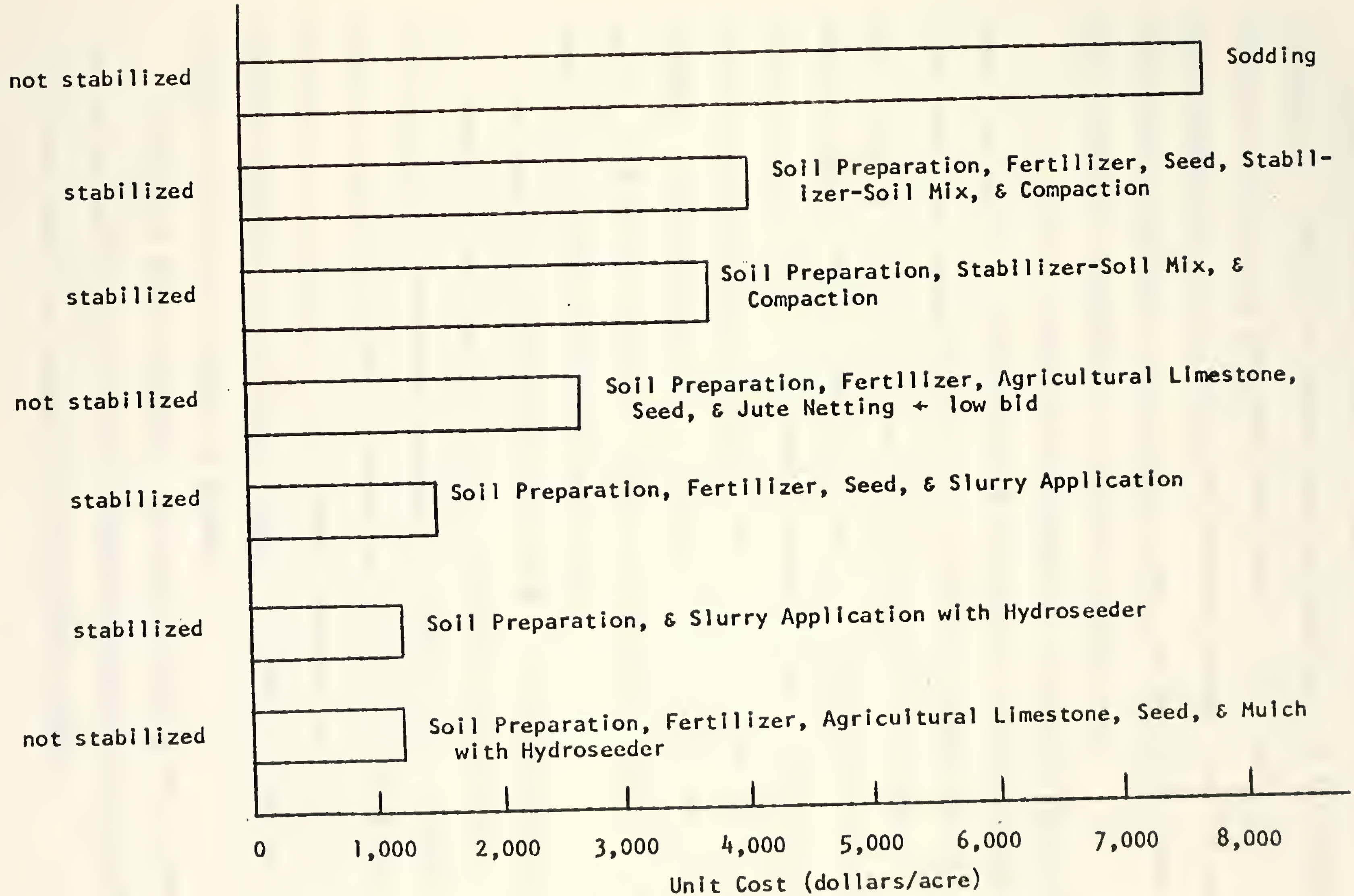


Fig. 39 Cost of Competitive Stabilization Methods

Figure 39 provides a graphical comparison of the unit cost estimates for sodding, for conventional hydroseeding, and for several different stabilization treatments considered in this report. In these comparisons, no distinction has been made between lime and cement stabilization treatments in the cost analyses, the stabilizer costs being essentially competitive on a percent weight basis.

It is seen that conventional hydroseeding of grass (bottom) and slurry application of stabilizer on a prepared soil surface (second from bottom) are comparable in cost, but the slurry method has the advantage of giving a quicker resistance to erosion. If grass is desired, seeding before a cement or lime-slurry application (third from bottom) results in only a 30 percent increase in cost. The next most inexpensive method shown is seeding with a jute net cover (fourth from bottom). Ludlow Textiles (Ref. 22) states that the total cost could be as low as \$.45 per square yard. This value should be taken as a lower bound estimate under competitive conditions.

The stabilization method involving mixing of additive and soil plus compaction would cost on the order of three times as much as the conventional hydroseeding treatment. Of course, such a method would provide the advantage of thorough and uniform distribution of stabilizer, thus giving rise to an almost immediate resistance to erosion, uniformly, over the area treated. If seeding is desired, the increase in cost is only about 10 percent.

Sodding was also considered. The cost of applying sod is twice that of the additive-soil mix plus compaction method, and approximately 6-1/2 times that of the conventional hydroseeding method.

Summarizing, it can be seen that the lime and cement stabilization methods are competitive with conventional erosion prevention techniques. The slurry stabilization method is competitive in cost to the conventional hydroseeding technique, with the marked advantage of quick erosion resistance. The stabilizer-soil mixture with compaction is a competitive method in relation to the method involving jute netting covering the seeded soil and is more economic than sodding. However, sodding has the advantage that the appearance of grass is immediate but, possibly, the erosion resistance is less.

SUMMARY AND CONCLUSIONS

It has been found possible, with small quantities of Portland cement or hydrated lime to reduce the erosion loss of all soils tested under a standardized severe rainstorm sequence. The standard storm testing program involved steady rainfall of 3-1/4 inches per hour on each of two consecutive days. The erosion as measured in this study was that due to raindrop impact only, the erosion loss being measured as that weight of soil removed from the specimen's surface by raindrop impact and divided by the specimen's original surface area to yield a calculated value representing the erosion loss per unit area.

The four soils used in this study were chosen to represent a range in composition, texture, and structure. The erosion results indicated that stabilization success does depend somewhat on the soil type.

Untreated soils exhibit a general trend of reduction in erosion loss with a reduction in compactive effort. The results indicated that the unstabilized heavy clay eroded significantly less than the other unstabilized soils, indicating that erosion loss partly depends on the soil type.

In general, resistance to erosion loss was highly satisfactory for all specimens mixed with one percent Portland cement and compacted to the equivalent of Standard Proctor density. Corresponding specimens

mixed with one percent lime achieved satisfactory erosion resistance but not until after a curing period of a week or more.

Reducing the compactive effort generally reduced the resistance to erosion only slightly, and it is apparent that successful stabilization can be achieved without full compaction. However, a longer curing period seemed to be required for specimens treated with one percent lime to attain good response under reduced compactive effort. There were some differences of note in stabilization effectiveness with the different soils tested, especially when treated with lime. Glacial Outwash soil and Tan Clay Till, as opposed to Blue Clay Till and Romney soil, experienced poor reduction in erosion loss at reduced compaction with lime treatment after short curing periods. As the curing period increased, the reduction in erosion loss became satisfactory, where for the other two soils it was excellent.

Untreated soil specimens (compacted at low density) which had a stabilizer-slurry poured on their surfaces resulted in reduced erosion loss. The reduction in erosion loss was excellent for cement and lime-slurry treatments on Blue Clay Till and Glacial Outwash soil (where the lime treated specimens experienced a delay in erosion resistance). Romney soil, the heavy montmorillonitic clay, experienced an increase in erosion loss accompanying the cement-slurry treatment but had excellent results with lime-slurry, in that erosion loss was reduced to an insignificant level. Stabilizer-slurry treatment, as tested here, showed good potential for field stabilization use in that it is easy to apply and the treatment results in a significant reduction in erosion loss.

It was found that grass was able to germinate and grow in soil stabilized by the methods previously discussed except for the compacted lime-soil mixes where the pH was apparently too high for the seed to germinate.

As indicated in the economic aspects section of this report, practical applications of stabilization methods are possible and may be economically competitive with conventional methods of providing erosion protection. Slurry treatment is less expensive than the additive-soil mix treatment. Costs were also found to be quite reasonable for projected methods involving a combination of stabilization plus grass seeding.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Arman, A. and Saifan, F., "The Effect of Delayed Compaction on Stabilized Soil-Cement," Highway Research Board Record, 198, pp. 30-38, 1967.

2. Catanach, R. B. and McDaniel, T. N., "Cement Stabilized Fill for Conduit Support," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, pp. 959-963, June 1971.

3. Catton, M. C., "Early Soil-Cement Research and Development," Journal of the Highway Division, American Society of Civil Engineers, pp. 1-16, January 1959; "Closure," pp. 67-75, March 1960,

4. Clare, K. E. and Cruchley, A. E., "Laboratory Experiments in the Stabilization of Clays with Hydrated Lime," Geotechnique, pp. 97-111, 1957.

5. Cooper, L. D., Locey, J., and Zoller, W. G., personal visit to the Roadside Development Division, Indiana State Highway Commission, Indianapolis, Indiana, October 1974.

6. Davidson, L. K., Demirel, T., and Handy, R. L., "Soil Pulverization and Lime Migration in Soil-Lime Stabilization," Highway Research Board Record, 92, pp. 102-118, 1965.

7. Davidson, D. T., Pitre, G. L., Mateos, M., and George, K. P., "Moisture-Density, Moisture-Strength and Compaction Characteristics of Cement-Treated Soil Mixtures," Highway Research Bulletin, 353, pp. 42-63, 1962.

8. Diamond S. and Kawamura, M., Soil Stabilization for Erosion Control, Joint Highway Research Project 74-12, Purdue University, West Lafayette, Indiana, 1974.

9. Diamond, S. and Kinter, E. B., "Mechanisms of Soil-Lime Stabilization: An Interpretive Review," Highway Research Board Record, 92, pp. 83- 102, 1965.

10. Eades, J. L. and Grim, R. E., "A Quick Test to Determine Lime Requirements for Lime Stabilization," Highway Research Board Record, 139, pp. 61-72, 1966.

11. Epps, J. A., Dunlap, W. A., Gallaway, B. M., and Currin, D. D., "Soil Stabilization: A Mission Oriented Approach," Highway Research Board Record, 351, pp. 1-20, 1971.

12. Fohs, D. G. and Kinter, E. B., "Migration of Lime in Compacted Soil," Public Roads, Vol. 37, No. 1, pp. 1-8, June 1972.

13. George, K. P., "Mechanism of Shrinkage Cracking of Soil-Cement Bases," Highway Research Board Record, 442, pp. 1-10, 1973.

14. Handy, R. L., "Cementation of Soil Minerals with Portland Cement or Alkalis," Highway Research Board Bulletin, 198, pp. 55-64, 1958.

15. Herrin, M. and Mitchell, H., "Lime-Soil Mixtures," Highway Research Board Bulletin, 304, pp. 99-138, 1961.

16. Herzog, A. and Mitchell, J. K., "Reactions Accompanying Stabilization of Clay with Cement," Highway Research Board Record, 36, pp. 146-171, 1963.

17. Ingles, O. G. and Metcalf, J. B., Soil Stabilization: Principles and Practice, Wiley, 1973.

18. Johnson, A. W. and Sallberg, J. R., "Factors that Influence Field Compaction of Soils," Highway Research Board Bulletin, 272, 1960.

19. Kawamura, M., Fundamental Studies on the Fabric of Soil-Cement Mixture and It's Mechanical Properties, Ph.D. Thesis, Kanazawa University, Japan, October 1970.

20. Kinter, E. B. and Diamond, S., "A New Method for Preparation and Treatment of Oriented Aggregate Specimens of Soil Clays for X-ray Diffraction Analysis," Soil Science, Vol. 81, No. 2, pp. 111-120, February 1956.

21. Lambe, T. W., "Summary of The Conference on Soil Stabilization," Massachusetts Institute of Technology Conference on Soil Stabilization, pp. 303-310, 1952.

22. Lightsey, G. R., Arman, A., and Callihan, C. D., "Changes in the Characteristics of Cement Stabilized Soils by Addition of Excess Compaction Moisture," Highway Research Board Record, 315, pp. 36-45, 1970.

23. Ludlow Corp., Control Erosion and Costs with Ludlow Soil Saver, Massachusetts, 1974.

24. Marks, B. D. and Haliburton, T. A., "Acceleration of Lime-Clay Reactions with Salt," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, pp. 327-339, April 1972.

25. Mitchell, J. K. and El Jack, S. A., "The Structure of Clay-Cement and its Formation," 14th American Clay Minerals Conference, Clay Mineral Society, Berkeley, California, August 23-24, 1965.

26. Murray, G. E., "Soil Stabilization by Chemical Means," Massachusetts Institute of Technology Conference on Soil Stabilization, pp. 107-117, 1952.

27. Noble, D. F., "Reactions and Strength Development in Portland Cement-Clay Mixtures," Highway Research Board Record, 198, pp. 39-56, 1967.

28. Pietsch, P. E. and Davidson, D. T., "Effects of Lime on Plasticity and Compressive Strength of Representative Iowa Soils," Highway Research Board Record, 335, pp. 11-30, 1962.

29. Portland Cement Association, Soil-Cement Laboratory Handbook, pp. 48-52, 1956.

30. Townsend, D. L. and Klym, T. W., "Durability of Lime-Stabilized Soils," Highway Research Board Record, 139, pp. 25-41, 1966.

31. Wang, J. W. H. and Kremmydas, A. H., "Use of Sodium Chloride in Reducing Shrinkage in Montmorillonitic Soil-Cement," Highway Research Board Record, 315, pp. 81-89, 1970.

32. Whitehurst, E. A. and Yoder, E. J., "Durability Tests on Lime-Stabilized Soils," Proceedings of the Thirty-First Annual Meeting of the Highway Research Board, pp. 1-12, January 1952.

33. Wilson, S. D., "Effect of Compaction on Soil Properties," Massachusetts Institute of Technology Conference on Soil Stabilization, pp. 148-158, 1952.

34. Young, R. A. and Wiersma, J. L., "The Role of Rainfall Impact in Soil Detachment and Transport," Water Resources Research, Vol. 9, No. 6, American Geophysical Union, pp. 1629-1636, 1973.

APPENDICES

APPENDIX A

RESULTS OF PRELIMINARY QUALITATIVE TRIALS TO DECIDE ON APPROPRIATE SLURRY CONCENTRATIONS

Untreated specimens were prepared using different compactive efforts and modifications as shown in Tables A1 and A2. The stabilizer-slurry concentration was varied in order to find that concentration which was low enough to be economical, easily applied, fluid enough to flow readily into the soil voids, and which resulted in a satisfactorily deep layer of stabilized soil.

A slurry concentration of 10 percent was chosen because it is economical and the stabilizer penetration was observed to be better at the smaller concentrations. It was decided that the lower compactive effort would encourage easy access of slurry into the soil because of the increased content of soil voids on the surface and the increased sizes of the voids.

Table A1 Results of Preliminary Qualitative Trials to Decide on Appropriate Slurry Concentrations with Cement

Sample	Percent Slurry	Stabilizer Weight (g)	Specimen Preparation	Dry Density (lb/ft^3)	Stabilizer Penetration
13	11.1	9	10 blows	94.1	very good
14	15	0	10 blows	93.5	good
15	20	9	hand pressed	77	reasonably good

Table A2 Results of Preliminary Qualitative Trials to Decide on Appropriate Slurry Concentrations with Lime

Sample	Percent Slurry	Stabilizer Weight (g)	Specimen Preparation	Dry Density (lb/ft^3)	Stabilizer Penetration
8	20	9	60 blows	122	poor
9	20	9	60 blows & scarification of surface	122	fair
10	20	9	60 blows, then broken, recompacted @ 10 blows	109.1	good
11	40	9	60 blows	122	poor
11_2	20	9	10 blows	94	reasonably good
12	20	9	60 blows, then broken, replaced by hand	86.3	good

APPENDIX B

X-RAY DIFFRACTION RESULTS

X-ray diffraction response was determined for each of the four soils used in this study.

A General Electric model XRD-5 diffractometer was used to examine the oriented aggregate specimens of the clay sized fraction (< 2μ). Using the procedure of Kinter and Diamond (1956), the soil was deposited from a suspension onto flat ceramic plates by means of centrifuging. To assist in the identification of the clay minerals, four specimens of each soil were prepared and treated with: (a) air drying; (b) glycerol solvation; (c) K^+ saturation; and (d) furnace drying at 550°C.

The following conditions were maintained on the diffractometer-recorder system: Ni filtered Cu Kα radiation generated at 50 kilovolts and 16 milliamps, beam slit = 1.0°, detector slit = 0.2°, and time constant = 2 seconds.

The results are shown in Figs. B1 through B4 and the interpreted clay minerals are listed in Table 1.

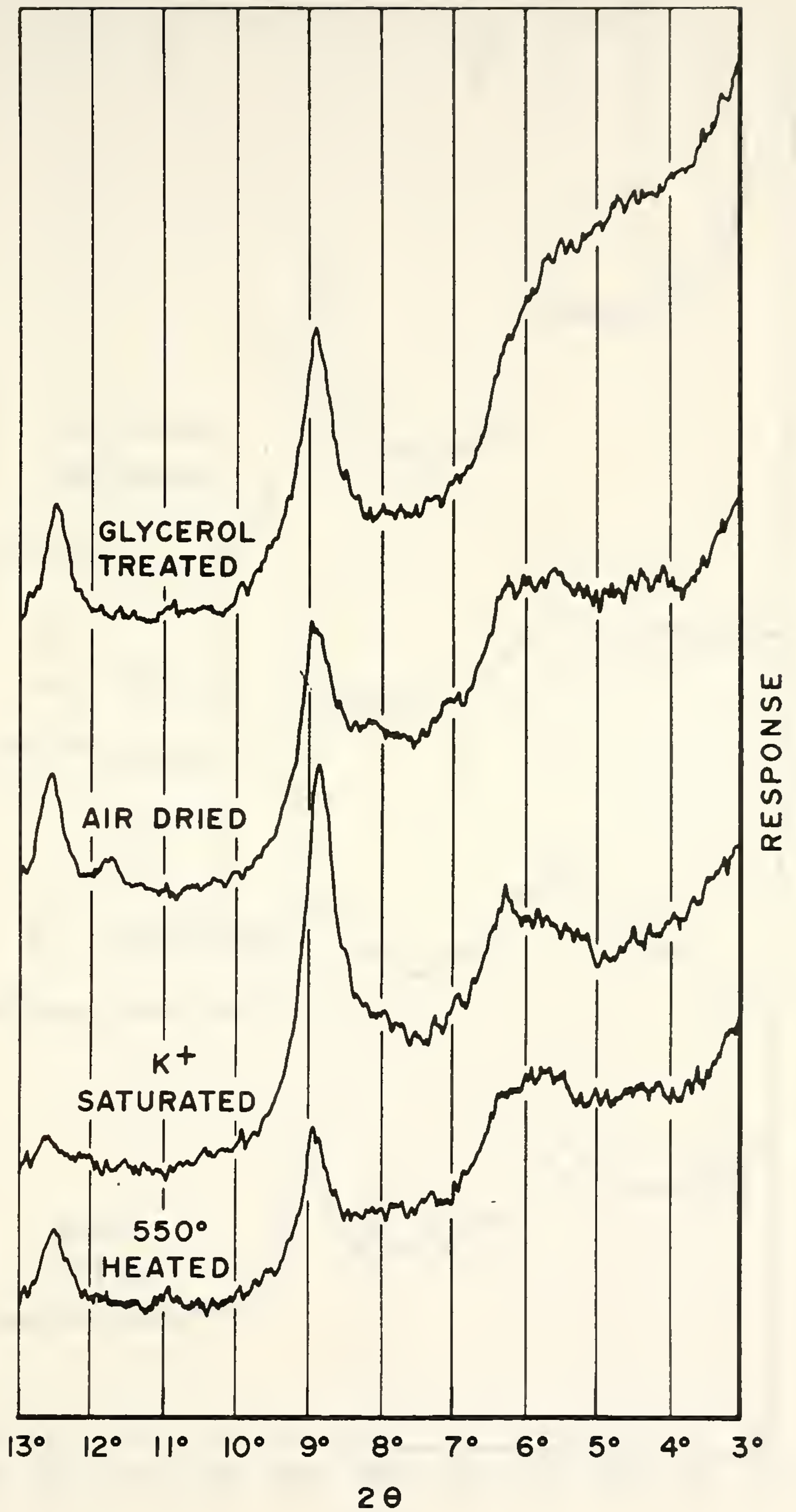


Fig. B1 X-ray Diffraction Results for Blue Clay Till

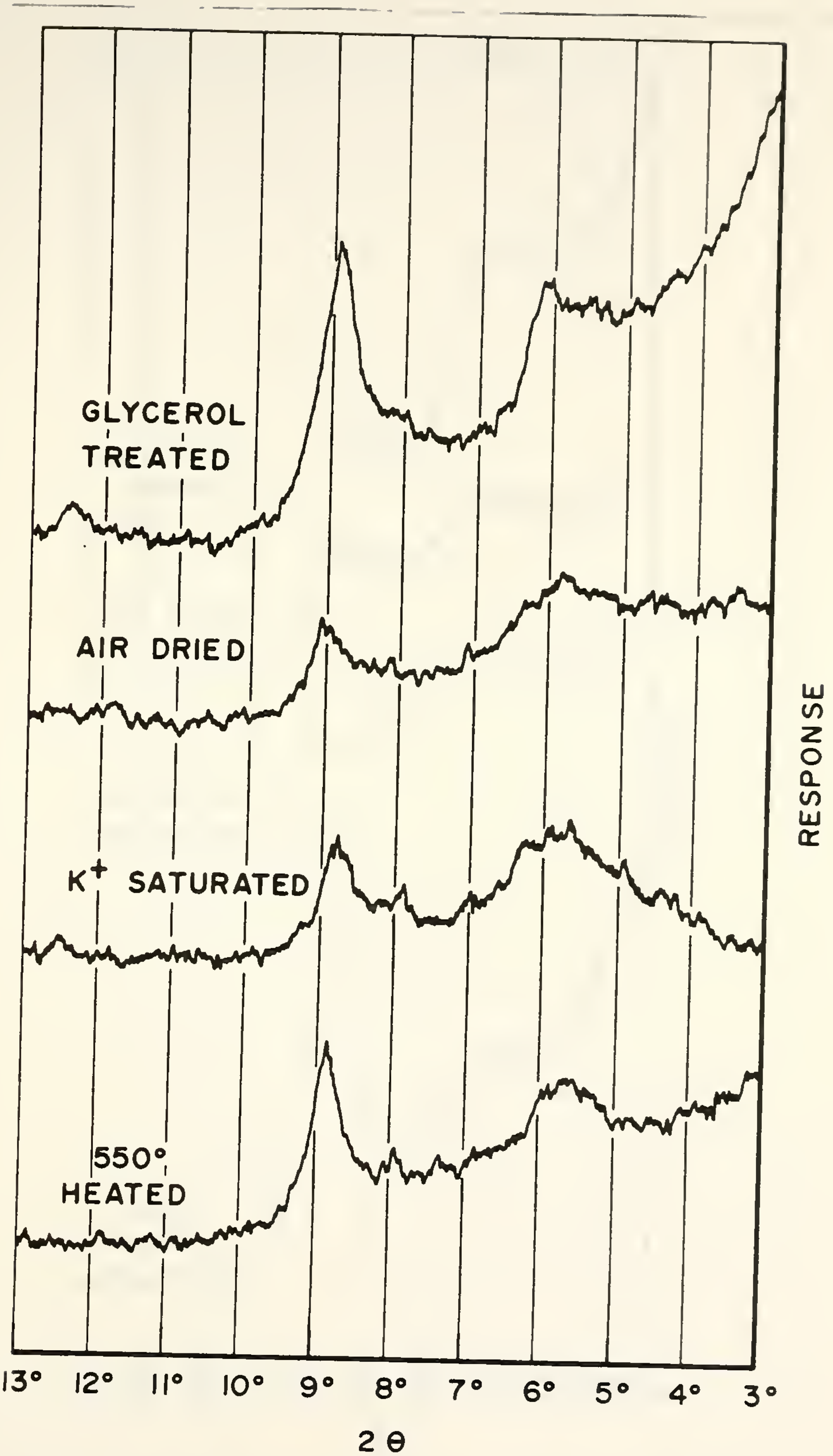


Fig. B2 X-ray Diffraction Results for Tan Clay Till

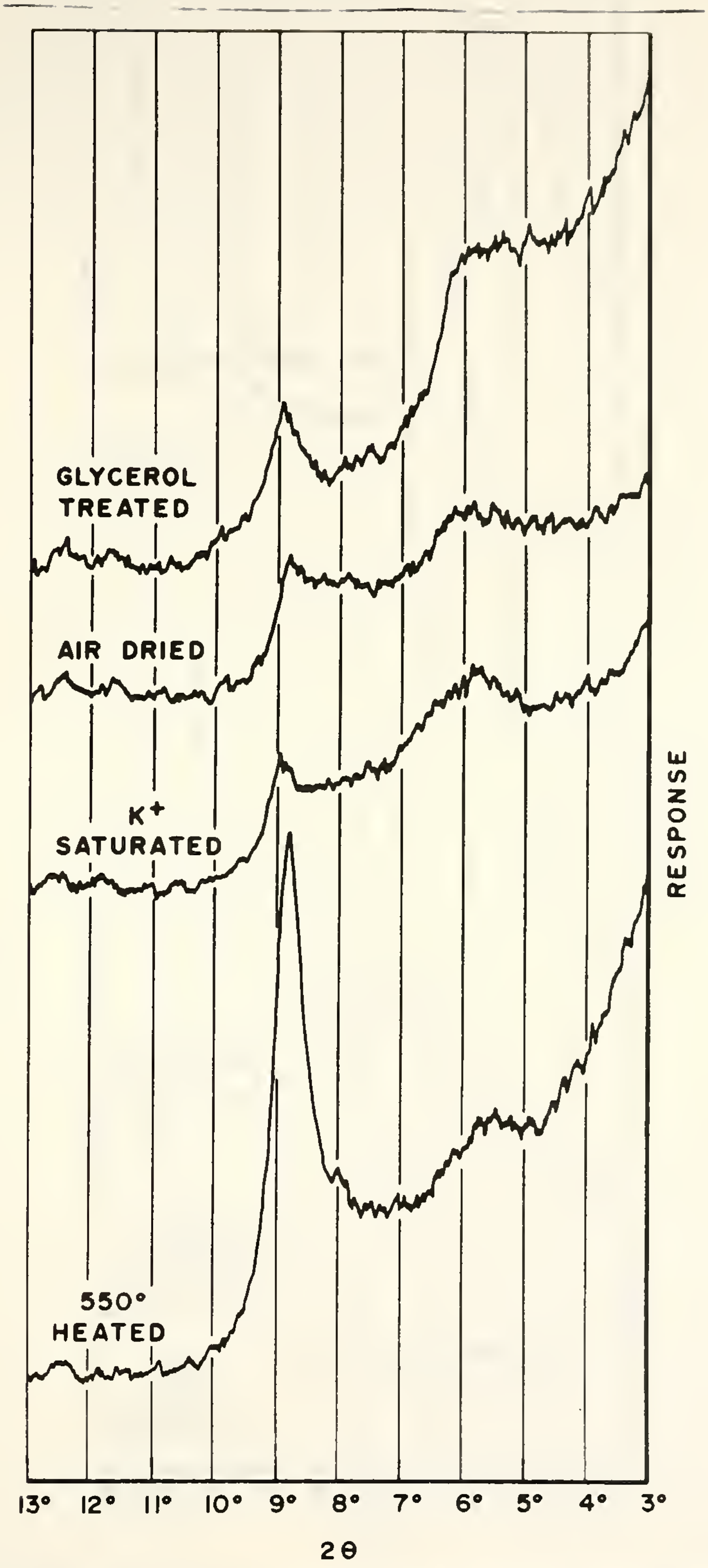


Fig. B3 X-ray Diffraction Results for Glacial Outwash

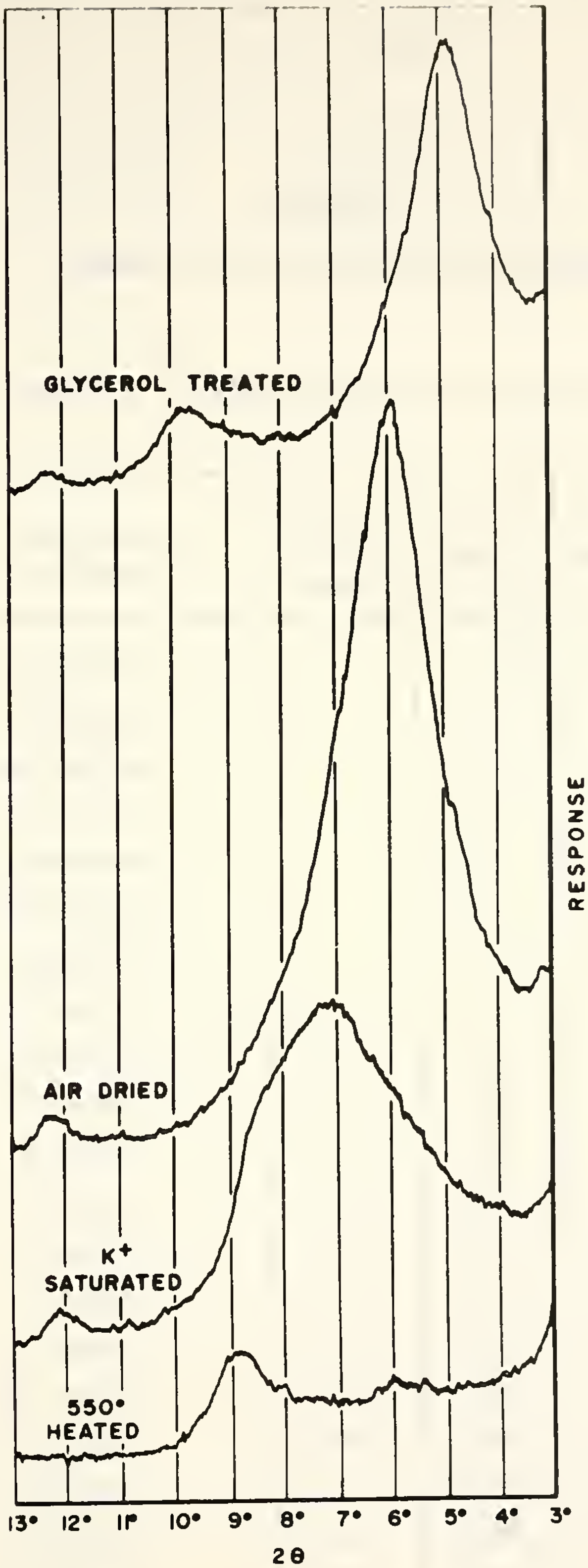


Fig. B4 X-ray Diffraction Results for Romney Soil

APPENDIX C

SUMMARY OF ALL EROSION TEST RESULTS

Table C1 Erosion Results for Blue Clay Till

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2) *
60	untreated		2.05	10	1.68
60	untreated		1.97	11.6	1.74
30	untreated		2.03	11.5	1.27
30	untreated		1.96	10.2	2.29
10	untreated		1.82	14	1.13
10	untreated		1.81	14.5	.88
8 @ 4" drop	untreated		1.55	14.3	1.32
8 @ 4" drop	untreated		1.54	12.7	.77
60	1% cement	7	1.85	9	.048
60	1% cement	3	1.86	7.9	.048
30	1% cement	7	1.84	11.6	.014
30	1% cement	3	1.82	13.6	.012
10	1% cement	7	1.72	13.4	.025
10	1% cement	3	1.71	13.4	.038
8 @ 4" drop	1% cement	7	1.32	14.6	.11
8 @ 4" drop	1% cement	3	1.30	14.3	.17
60	1% lime	28	1.90	9.1	.018
60	1% lime	7	1.96	11.5	.014
60	1% lime	3	1.88	11.2	.21
30	1% lime	28	1.70	11.8	.024
30	1% lime	7	1.73	11.2	.21
30	1% lime	3	1.69	11.2	.28

Table C1, cont.

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2) *
10	1% lime	28	1.63	14.7	.080
10	1% lime	7	1.55	13.8	.49
10	1% lime	3	1.55	13.1	1.05
8 @ 4'' drop	1% lime	28	1.25	14.3	.22
8 @ 4'' drop	1% lime	7	1.40	15.6	.56
8 @ 4'' drop	1% lime	3	1.29	13.8	.76
10	10% cement slurry concentration	7	1.85	14.3	.053
10	10% cement slurry concentration	3	1.84	14.1	.40
8 @ 4'' drop	10% cement slurry concentration	7	1.65	15.2	.049
10	10% lime slurry concentration	28	1.83	16.5	.015
10	10% lime slurry concentration	7	1.81	15.6	.020
8 @ 4'' drop	10% lime slurry concentration	32	1.39	13.9	.030
8 @ 4'' drop	10% lime slurry concentration	5	1.65	16.1	.044

Table C2 Erosion Results for Tan Clay Till

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2)*
60	untreated		2.00	10.2	2.26
30	untreated		1.92	10.1	1.82
10	untreated		1.82	12.3	1.76
8 at 4'' drop	untreated		1.83	14.8	.744
60	1% cement	7	1.93	9.2	.008

Table C2, cont.

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2)*
60	1% cement	3	1.97	9.8	.021
30	1% cement	7	1.88	11.1	.008
30	1% cement	3	1.85	10.3	.018
10	1% cement	7	1.70	12.3	.034
10	1% cement	3	1.66	11.9	.090
60	1% lime	28	1.95	10.5	.008
60	1% lime	7	1.91	8.7	.67
60	1% lime	3	1.93	9.7	.12
10	1% lime	28	1.65	12.4	.27
10	1% lime	7	1.61	12.1	1.58
10	1% lime	3	1.69	12.6	1.67

Table C3 Erosion Results for Glacial Outwash Soil

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2)*
60	untreated		1.84	11.4	2.53
10	untreated		1.70	14	2.42
8 @ 4" drop	untreated		1.68	14.1	1.91
60	1% cement	7	1.86	11.1	.046
60	1% cement	3	1.83	10.2	.072
10	1% cement	7	1.53	12.8	.22
10	1% cement	7	1.62	10.2	.12
10	1% cement	3	1.57	12.9	.19
8 @ 4" drop	1% cement	7	1.65	13.9	.091
8 @ 4" drop	1% cement	3	1.75	16.5	.43
60	1% lime	28	1.86	11.4	.006

Table C3, cont.

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2) *
60	1% lime	7	1.84	11.5	.066
60	1% lime	3	1.94	10	.063
10	1% lime	28	1.61	13.7	.058
10	1% lime	7	1.59	12.5	.672
10	1% lime	3	1.65	12.9	1.052
8 @ 4'' drop	1% lime	28	1.75	16	1.14
8 @ 4'' drop	1% lime	7	1.71	13.8	1.64
8 @ 4'' drop	1% lime	3	1.71	14	.66
10	10% cement slurry concentration	7	1.73	12.2	.040
10	10% cement slurry concentration	3	1.69	11.6	.11
8@ 4'' drop	10% cement slurry concentration	7	1.64	14.2	.13
10	10% lime slurry concentration	28	1.73	13.2	.087
10	10% lime slurry concentration	7	1.90	13.2	1.73

Table C4 Erosion Results for Romney Soil

Compactive Effort (blows)	Stabilizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2) *
60	untreated		1.54	21.9	1.076
10	untreated		1.25	31.3	.16
10	untreated		1.27	34.1	.24
60	1% cement	7	1.52	23.8	.013
60	1% cement	3	1.58	24.9	.15
10	1% cement	7	1.13	28.3	.15

Table C4, cont.

Compactive Effort (blows)	Stablizing Treatment	Curing Period (days)	Dry Density (g/cm^3)	Water Content (%)	Erosion per Area (g/cm^2) *
10	1% cement	3	1.16	29.2	.15
10	3% cement	7	1.07	34.1	.060
60	1% lime	28	1.53	21.5	.45
60	1% lime	7	1.46	22.9	.42
60	1% lime	3	1.52	22.4	.54
10	1% lime	28	1.22	29.9	.35
10	1% lime	7	1.15	29.8	.29
10	1% lime	3	1.17	30.1	.42
10	10% cement slurry concentration	7	1.23	34.2	.30
10	10% cement slurry concentration	3	1.25	35.3	.31
10	10% lime slurry concentration	28	1.24	37.8	.008
10	10% lime slurry concentration	7	1.26	32.8	.042

*Average of three replicates

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